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WORKSHOP ON CLOSED MOLD MANUFACTURING OF HIGH PERFORMANCE COMPOSITE MISSILE STRUCTURES

Janet Sater

November 1995

Prepared for
Ballistic Missile Defense Organization

INSTITUTE FOR DEFENSE ANALYSES
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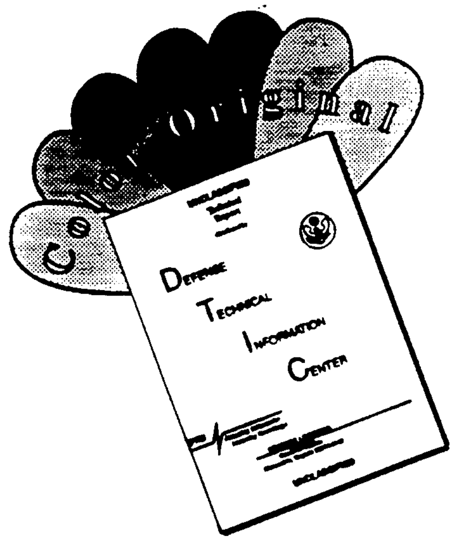

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PREFACE

LtCol Michael Obal of the Ballistic Missile Defense Organization Materials and Structures Office manages a wide variety of advanced technology and demonstration programs addressing needs for various systems. A number of demonstration programs have been initiated over the past few years. These projects include fabrication and test of adaptive structures for jitter control and sensor system performance, and light weight spacecraft and missile structures. Advanced polymer composites have been selected for fabrication of many of these structures due to their high performance capabilities and to the potential for reduced weight. One of the major drawbacks of this class of composites, however, has been the high cost of manufacturing components. Closed mold manufacturing processes such as resin transfer molding or matched metal net-shape molding offer potential low-cost methods for making such components for missiles. A workshop involving missile producers, material suppliers (resins, preforms, prepregs), and parts fabricators was planned, in part, to promote communication among the appropriate groups. The agenda was put together by LtCol Michael Obal and Dr. Janet M. Sater (Institute for Defense Analyses) to address technical issues and limitations associated with closed mold manufacturing of high performance polymer composites for missile applications.

The workshop was hosted by IDA on May 15–16, 1995. IDA was requested under the BMDO "Materials and Structures Development in Support of the Strategic Defense Initiative" task to participate in the workshop and to prepare a proceedings to document the content of the workshop. This effort was subsequently carried out by Dr. Janet M. Sater with input from LtCol Michael Obal and Dr. John Stubstad (The Aerospace Corporation).

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I. INTRODUCTION

LtCol Michael Obal of the Ballistic Missile Defense Organization (BMDO) Materials and Structures (M&S) Office manages a wide variety of advanced technology and demonstration programs that address needs for various systems. Included among the demonstration programs are (1) fabrication and test of adaptive structures for jitter control and improved sensor system performance and (2) lightweight spacecraft and missile structures. Advanced polymer composites have been selected for fabrication of these structures because of their high-performance capabilities and the potential for reduced weight. One of the major drawbacks of this class of composites—and of primary concern to potential end users—has been the high cost of manufacturing components. Closed mold manufacturing processes such as resin transfer molding (RTM) or matched metal net-shape molding (MMNM) offer potential low-cost methods for making such components for application in missile systems. In response to these concerns, LtCol Obal requested that the Institute for Defense Analyses (IDA) organize a workshop to address material availability, processability, quality, data, fabrication and test experience, and other issues that prevent users from adopting these materials. This workshop involved missile producers; resin, preform, and prepreg suppliers; and parts fabricators. It served as a forum to promote communication among the appropriate groups and to identify technical issues and limitations associated with these manufacturing methods.

The document follows the order of the final revised agenda found in Appendix A, which also lists the meeting attendees. Section II contains summaries and discussions of missile system producer perspectives, Section III contains material supplier perspectives, and Section IV contains parts fabricator perspectives. Appendixes B through E contain copies of the charts for Sections I through IV, respectively. Section V contains the final summary and conclusions.

A. LtCol MICHAEL OBAL, BMDO

LtCol Obal began by stating that materials insertion is difficult, noting that experience indicates that not everyone talks to the users. He also said that BMDO was "working technologies that we hope industry will run with," emphasizing that the desire is

"to find out where the problems and uncertainties are." He then provided an overview of BMDO activities in the development and demonstration of polymer composite manufacturing methods, specifically closed mold manufacturing. This manufacturing technology is believed to be cost-competitive with metals for high-performance interceptor structures and may offer manufacturing agility and cost-effective production of multi-functional structures.[1] When one considers the different types of matrix materials (polymers, metals, or ceramics) and reinforcements (discontinuous or continuous forms), the potential growth in general use is most obvious for the continuous fiber-reinforced polymer composites (p. B-3). LtCol Obal indicated that for this category, in his view, materials and process research and composite design tool development represent mature capabilities (p. B-4), and costs associated with these capabilities are fairly well understood. However, maturity of manufacturing and achievement of low manufacturing costs are affected by industry demand. He felt that industry is reluctant to accept these high-performance composites primarily because of a lack of products demonstrating competitive manufacturing costs; therefore, BMDO is putting its resources in manufacturing. Obal noted that "if we're not heading toward reduced cost, it's not useful for the user." Page B-5 illustrates several different processes for making polymer composites, using either discontinuous or continuous reinforcements. The two processes of particular interest to BMDO are RTM and MMNM (p. B-6). The MMNM process appears to offer somewhat more flexibility in terms of component shape and materials.

BMDO initiated its Composite Technology program (p. B-7) in Fiscal Year (FY) 1987, with a program emphasis on engineering requirements for lightweight and extremely stiff structures and design tools development. From this effort, MMNM and textile braiding were selected for interceptor and propulsion components, respectively. In FY 1990, issues associated with multi-functional requirements and manufacturing costs began to be addressed. More recently, efforts have been focused on manufacturing cost reductions, for example, achieving multi-functional capabilities in essentially a single composite curing step, automating mold closure, and so forth. The chart on p. B-8 compares the cost of a hand-laid composite structure with projected costs of one manufactured by MMNM (tool costs are amortized over 500 or 1,000 units). Primary differences

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1 Multi-functional structures refer to structures that have more than one capability, i.e., the ability to handle loads, thermal management, electromagnetic interference (EMI), charging, lightning strike protection, and others.

between the two processes are the elimination of the assembly and secondary operations[2] and a reduction in quality assurance costs.

One specific example of a structure fabricated under the M&S program is a missile avionics container (p. B-9). This structure is multi-functional because it carries load, handles thermal management, electromagnetic interference (EMI), and ground plane shielding functions. Multi-functionality for the EMI and ground plane shielding can be achieved through several techniques illustrated on p. B-10. One example is nickel-coated graphite fiber woven into a cloth that is molded in with the other composite layers during the MMNM process. This technique provides excellent EMI shielding for flat shapes and good ground plane shielding. Another example of a structure is the solid propellant Divert Attitude Control System (DACS), an integral propulsion/structure concept (p. B-11) in which the individual grain cartridges are located in the aeroshell structure.[3] The Endo-atmospheric Flight EXperiment (EFEX) program is expected to demonstrate improved airframe structural thermal integrity up to 900 °F, lower production costs for braiding, and automated fiber placement. The structure consists of a net-molded substructure and braided heat shield, which will be co-cured (p. B-12). LtCol Obal mentioned that manufacturing techniques have been developed in other programs to fabricate adaptive structures that contain embedded sensors and actuators in polymer composites as shown on p. B-13. These sensors and actuators provide other types of functionality to the structure.

Candidate applications for closed mold manufacturing cover a broad range of categories ranging from missiles to land vehicles to electronic enclosures, among others (p. B-14). The process appears to have generic features that make it attractive from an agile manufacturing point of view (p. B-15): rapid tool production, quick convergence to an optimal process, fast tool changes to produce a mix of parts, and process control and in-situ non-destructive inspection (NDI).

The final segment of this presentation discussed the lessons learned by the aircraft industry about composite structures technology,[4] with Obal noting that no loss of life has been attributed to composite part failure. These lessons are grouped under the following general headings:

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2 The tool can incorporate all geometric features of the structure including penetrations, inserts (fastener mounting points), foam sandwich bulkheads, and so forth.

3 As indicated in the schematic, opposing cartridges burn to provide pitch/yaw stability for the interceptor.

4 These lessons derive from NASA-Langley Report #4620.

- Organizational issues (pp. B-16–B-17)
- Structural design, analysis, and test (p. B-18)
- Materials and processing (p. B-19)
- Manufacturing and tooling (p. B-20)
- Quality control (p. B-21)
- Supportability (p. B-22).

Only one example of each is provided here. Please review the others.

The lessons learned are as follows:

- A concurrent engineering approach involving generalists with multi-disciplinary experience appears to have been most successful in ensuring the insertion of composites. This approach leads to resolution of problems early in the development phase, reduces costs of rework and modifications, and enables designers to become familiar with relevant manufacturing and quality control technologies, material capabilities, and so forth.
- The most successful programs use a building block approach for development. Design, fabrication, and test of structural components were accomplished in steps to identify problems early in the program with the smallest investment in tooling and test complexity. This approach does, however, require realistic schedules.
- Conducting a materials development program in conjunction with a product development program creates undue risks.
- Designing for producibility is essential because the assembly and fabrication costs are determined by the selected design/manufacturing process.
- Focusing quality inspection and process control on those aspects of the process that have a direct bearing on part quality and performance is critical.
- Supportability is generally not adequately addressed during design. In fact, most damage occurs during assembly and routine maintenance.

B. JANET M. SATER, IDA

Dr. Sater began by describing the overall workshop objectives (p. B-24): to increase communication among end users, material suppliers, and composite parts manufacturers and to identify technical issues and limitations associated with the application and closed mold manufacturing of polymer composites for missile structures. To address these objectives properly requires the participation of several groups of people: missile system producers and designers, material vendors, and composite parts fabricators.

Dr. Sater reviewed the subject areas to be addressed by each group, noting that strong sales pitches were discouraged.

Missile producers were asked to describe a thought process for design and manufacturing (p. B-25). When one designs a missile system, many options for materials must be evaluated. What interests us, to some degree, is the selection process. Why are some materials chosen over others? More specifically, why are composites not selected? Therefore, missile producers were asked to provide information required for the application of advanced composites in primary and secondary structures for missile systems. This information included data on processes, properties, qualification tests, and any lack thereof. Expectations for operational functions of such structures also were desired. For example, what capabilities should the composite provide to the structure (ability to handle loads, thermal management, EMI, charging, lightning strike protection)? Other issues that need to be addressed for application and production include program schedules, cost sensitivities, production lot sizes, expected lifetimes, assembly/disassembly cycles, reparability, disposal, and so forth.

Preform suppliers were asked to describe available fiber options and architectures, with a particular focus on manufacturing limitations (p. B-26). These limitations might include preform size, achievable fiber volume fractions, minimum fiber bend radii, fiber sizing, and equipment availability. Information on resin options and associated processing limitations and a description of methods to address problems with existing resins was requested from resin suppliers (p. B-27). Other items to be addressed included drivers for developing new resins and government regulations or other restrictions that may affect supply. Prepreg suppliers were asked to describe available fiber and resin combinations and product forms and the manufacturing limitations with each (p. B-28). All the materials suppliers were requested to describe methods used to assess quality of their respective products.

Composite parts fabricators were asked to describe difficulties they experienced making polymer composite parts using particular closed mold manufacturing methods, especially material uniformity and processing-related difficulties (p. B-29). Results from additional testing [such as density (porosity)] and other physical or mechanical properties by materials (matrix and fiber architecture) and a description of desirable new materials wre requested. Since cost is of particular importance to the end user, the parts fabricators also were asked to estimate current and projected costs for projected production lot size.

Finally, they were asked to provide lessons learned from their experiences that will increase the confidence of missile producers in these composite structures.

II. MISSILE SYSTEM PRODUCERS

A. LOCKHEED MARTIN MISSILES & SPACE COMPANY (LMMSC), TOM ANDERSON

Tom Anderson provided examples of missile weapons systems being developed by Lockheed Martin: Trident II, Exoatmospheric Re-entry Interceptor Structure (ERIS), and Theater High Altitude Area Defense (THAAD) (p. C-2). He noted the use of a metallic end ring (lower left corner, p. C-2) to protect the composite structure during missile tear-down and build-up. The ERIS base frame (bottom center) is a honeycomb structure. LtCol Obal inquired about cost implications for this type of structure. The reply was that it was very labor intensive. The first ground test unit of THAAD is shown in the lower right corner. It contains a DACS and is covered by a heat shield (a fibrous silica layer). The inner surface of the composite shell has close tolerances. The design approach is simpler, and the design is also similar to the actual flight vehicle. In response to questions from LtCol Obal, Mr. Anderson indicated that dollies are used during installation and assembly of missiles,[1] noting that much more opening and closing[2] occurs during the research and development (R&D) and Engineering and Manufacturing Development (EMD) phases of a program.

LMMSC has demonstrated capabilities in the design, analysis, fabrication, and testing of advanced materials and structures (p. C-3). Particular skills include nosetips and heatshields, shrouds and missile bodies, thermal management, and among others. Material and Process Engineering and Engineering Development laboratories are responsible for development, characterization, and control.

Appendix C, p. C-4, illustrates schematically the team product design approach used by Lockheed Martin (LM).[3] Mission requirements are defined at the product team level and flowed down to other teams. The structures team is responsible for design integration to ensure that the structure meets everyone's requirements. The concept phase

1 These missiles are designed for a 20 year life.

2 Mr. Anderson indicated there are on the order of 45 openings during missile assembly and test phases.

3 Mr. Anderson indicated that for the THAAD program the teams have been maintained: previously the manufacturing people were moved to fabrication and production.

also addresses manufacturing. Trade studies are performed at this stage, and materials are down-selected. The selected materials are completely characterized, typically by subcontractors, to create A and B allowables. Mr. Anderson noted a "not-invented-here" attitude about data, particularly with respect to composites, since there is a lack of standardization. Most companies have their own proprietary database.

At this point, some questions were raised about details of the material selection and evaluation process. Dr. Mohan Aswani (Aerospace) mentioned that developing B allowables for several materials is very expensive and wondered if LM did a trade study and then fabricated and tested a component. After the requirements are passed to the Materials and Process (M&P) team, candidate materials are selected and screened. Prior experience is an important factor.[4] Only one material is selected by the structural design team for full characterization at the coupon level. A workshop participant asked a question about the role of M&P in material selection. The immediate answer was that the Mission team includes M&P representatives who participate in the team decision on materials. As shown on page C-5, the M&P team also screens a variety of processes in parallel with the material development activities. The team uses an integrated approach considering other components, environments, and so forth.[5] The filter for using composites consists of the mission requirements combined with the costs. Other important M&P team activities include developing design and process control data and providing the material and process specifications and detailed drawings. They also are ultimately involved in hardware fabrication. Subcontractors are important because they provide either materials or components. All subcontractors are required to provide process documentation, proof of process, notification of process changes, and lot/component traceability (p. C-6). LtCol Obal inquired, in particular, about inspection: Mr. Anderson replied that LM "would like to get rid of this, but it probably won't happen." One hundred percent inspection is required, especially for components. Subcontractor process discipline is critical. Dr. Aswani asked the following question: If a subcontractor came to LM and said that he would sell a part that meets with requirements at the half the current price but would not provide documentation, would LM accept it? The answer was an emphatic no! "Cost is not the object." In response to a question asked by LtCol Obal on receiving inspection, Mr. Anderson noted that limited data are taken and records are kept on a lot-by-lot basis.

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[4] Thirty combinations of materials were considered for the THAAD, including composite made using M40J and MSX graphite fibers.

[5] There were separate teams for the forebody, shroud, and structure.

Mr. Anderson next described LM's experience in the production of composite components. A total of 82,408 components have been made using hand lay-up and either press molding or autoclave molding. Press-molded components include, among others, third stage rings, nose fairing guides, and miscellaneous brackets and stiffeners for the Trident I C4 missile. The primary driver for using composites for the third stage and equipment section was weight. Composites worked well for thin sheet applications and where there were several repetitive parts such as brackets. Mr. Anderson noted a reject rate of 20 percent on press-molded parts. When queried about the reject rate, Mr. Anderson attributed the reject rate to tool design, saying that the "tool defines the quality of the parts." LtCol Obal mentioned that SPARTA has developed "an integrated approach[6] to everything that affects the part for tool design." This approach would evolve at a larger company by different organizations within the same company working together. Autoclave-molded components include, among others, primary structure shell, motor support cones and rings, and motor equipment modules for the Trident I C4 missile and the primary structure shell, main beam, and stiffeners and ribs for the Trident II D5 missile.[7] Autoclave molding allowed for larger, more complex parts. Observed reject rates were on the order of 4 to 6 percent. In response to an inquiry about reject rates from Mr. John Harrell of McDonnell Douglas Aerospace (MDA), Mr. Anderson indicated the primary rejection criterion was porosity, attributed to the fact that LM was using a low viscosity resin. In looking at cost percentages for a molded part (p. C-8), it is clear that for the steps[8] involved in making a composite component, hand lay-up is the most expensive step. LM is focusing its efforts on this step. LM showed a potential 18-percent savings by using a closed mold process. Savings derive from reduced vacuum bagging and part trimming.[9] LtCol Obal mentioned that the Japanese had been approached about the possibility of using robotics to help with lay-up of the composite for a closed mold process. The Japanese responded that using robotics would be extremely difficult for complex molds.

Mr. Anderson discussed the fact that untried manufacturing technologies, as is often true of composite processes, raise concerns and increase risks for a program. The fact that a longer learning curve does not exist for new fabrication technologies also prevents composites from being used. LtCol Obal then inquired about methods to bring

6 They use a requirements-driven, systems approach.

7 Cost was a particularly important issue for the Trident II D5.

8 The listed steps are hand lay-up, vacuum bagging, part trimming, mold cleaning, and curing.

9 Mr. Anderson mentioned that one of the primary benefits of composites was part consolidation.

manufacturing people up to speed on new technology. The speaker replied that the manufacturing people would not be brought up to speed because LM "wouldn't try something new on THAAD." However, he mentioned later that familiarizing manufacturing people with new technology is less of a problem at the component and subsystem level. There are other possibilities, of course. One option is a block change approach. The baseline component would be metal, and a replacement composite part would be worked until familiarity with new technology was achieved, at which point the composite part would be introduced. Other obstacles that prevent implementation of closed mold manufactured parts include the initial limited program quantities, which drive low, nonrecurring cost processes; limited development spans, which require mature materials and processes; and customer configuration management requirements, which promote no-change policies.

Mr. Anderson provided two sets of recommendations: one for technology organizations and one for project offices. He emphasized the importance of funding technology programs *in time* for program consideration and with the involvement of primes and suppliers. He also identified the standardization of data development methods and having that standard database available to all users. Steve Hackett (3M) asked about the utility of the Suppliers of Advanced Composites Materials Association (SACMA) test methods being developed through support from companies within SACMA. According to Mr. Hackett, these methods seem to be fairly well accepted by the aircraft community. Few of the workshop attendees appeared to be familiar with these test methods. Recommendations for the project offices included making producibility a contract item and allowing for producibility "block upgrades" in each contract phase, as is the case for THAAD.

B. LORAL VOUGHT (LV) CORPORATION, T. HO

Dr. Tzu-Li Ho is the manager for stress analysis at LV. He participates in material and vendor selection. LV also uses a team approach. Teams, "put together on a project-by-project basis," are essentially an autonomous group. The program office and program manager, however, have ultimate authority. They control cost, schedule, and weight and performance requirements. The structural designer must conform to the person/group who makes the system performance decisions.[10] Supportability and maintainability also are represented on the team. During Phase 1 R&D, only one or two structures are built,

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10 Apparently, the structure typically makes up about 10 percent of the system cost and 20 percent of its weight.

mostly to test whether the basic concept works. In this stage, "cost is no object really." During the EMD phase, producibility is improved. The team also strives to achieve the required performance and to reduce weight. In the production phase, cost is a primary concern. Dr. Ho observed that there is "a constant struggle between the different disciplines to reach a compromise."

Page C-12 shows some examples of systems with which LV has been involved. Included among these systems are the Army Tactical Missile System (ATACMS), the HyperVelocity Missile (HVM), the VT I (French), the Multiple Launch Rocket System (MLRS), and the space shuttle. Composite parts used in these systems include shell bodies (polymer composites), control surfaces [metal matrix composites, carbon/carbon (C/C), ceramics], nose/radome parts (polymer composites, ceramics), and rocket motors for missiles, launch pod containers [for multi-element radiometer system (MERS)], and C/C leading edges and nose for the space shuttle. About 80 percent of these parts are fabricated out-of-house. Most C/C parts are made in-house. All the polymer composite parts are fabricated through vacuum bag/autoclave methods. LtCol Obal asked if the precision of the part was not as critical as for some other applications. Dr. Ho replied that such a statement was not quite correct. The particular composite selected for a given application depends on the particular missile system. In response to a question from Gary Wonacott (Vanguard Composites), Dr. Ho indicated that composites were used for internal structures from time to time, but he did not know the weight percentage of such structures in a system. Dr. Ho added that weight was a critical concern because a complete redesign is necessary if a system is overweight.

A critical design driver in material selection is dimensional stability with respect to both temperature[11] (arising from the high missile speed) and manufacturing (warpage arising from residual stresses). Structural design considers these issues in detail (p. C-14). Thermal expansion, oxidation resistance (especially erosion),[12] chemical compatibility, duration,[13] and temperature levels are examined to assess the high-temperature compatibility of the material with the operational environment. Material processability and tooling design are evaluated to determine the manufacturer's capability. Structural capability of the

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[11] The operational temperature range of the launch pod is –60 to 180 °F. For a missile, it could range anywhere from –50 to 1,800 °F, depending on the particular system.

[12] The test involves heating the leading edge of a fin. If the fin contains a gas bubble, rapid expansion of the gas during fin heating may cause an explosion leading to fin blow-off.

[13] Since there are typically limited data on this LV performs its own testing. Heating a graphite-epoxy fin at 400 °F for 1 minute appears to be an adequate test since missiles have a relatively short life.

material is determined by evaluating strength, stiffness, durability, and nonlinear response[14] at temperature. Finite element modeling (FEM) is critical for test and evaluation (T&E). LtCol Obal mentioned that design of joints to operate under these high-temperature conditions is an issue. Dr. Ho indicated flight tests will be conducted for an instrumented, composite testbed. These structures are expected to undergo heating that will allow LV to evaluate the structural capability of these materials at temperature and to assess effects of the operational environment on performance. Dr. Ho also mentioned that new materials—fiber-reinforced composite materials, C/C, special anisotropic structures—on the market will be considered in a concept phase. Loads and other system features are derived from design criteria. Analysis tools such as software, design allowables, and other literature are critical. He indicated allowables are difficult to obtain (e.g., practical use of fracture mechanics for determining ceramics allowables). Dr. Ho said that the composites vendor with whom LV is working does have models for tool design. The primary issue in this situation is whether the company and vendor tool models can speak to each other. He also remarked that the two companies were exchanging drawings at present and that LV was trying to computerize drawings so that the most current design would be accessible. Dr. Ho emphasized the importance of T&E of *parts*: Testing of starting materials is not sufficient to ensure component or system performance. In response to a question about safety, Dr. Ho replied that the factor of safety is applied to predicted part performance. If the designer does not know what is happening in the manufacturing process and/or plant, his analysis can be wrong.

Natural environments of interest to a missile designer (p. C-16) include temperature and thermal shock, altitude, rapid decompression, various forms of water (ice, snow, hail, rain, sea water, humidity), sand and dust, wind, and biological organisms (fungi, bacteria). These environments must be considered for all missile parts. It is interesting to note that essentially all of these natural environments are important considerations in the design of the canister and the Missile Monitor System (MMS). A smaller subset is relevant to the missile itself. Induced environments from mechanical shocks, vibration, and acceleration are also of concern in missile design (p. C-17). Effects of these environments on missile systems vary since no two missile designs have the same requirements.

Advanced materials being considered for the PATRIOT Advanced Capability-3 (PAC-3) missile structure, illustrated on p. C-18, include an Infrared Transparent Barium-

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[14] There usually are very little data available on nonlinear response, particularly with respect to temperature effects.

Alumino-Silicate (IRBAS) ceramic,[15] filament-wound graphite fiber-reinforced epoxy, and C/C. LV has had some difficulty with the ceramic. Apparently, it is a "structural nightmare." Missiles are carried in the structure shown on p. C-19. This particular structure is a 4-pack canister (it carries four missiles). The "baseline" material is a gr/epoxy composite; the back-up material for the canister is an aluminum honeycomb. Damage is an issue with this material, but the predicted cost is lower.[16]

Dr. Ho provided a schematic of the T40 graphite fiber-reinforced-epoxy motor case (p. C-21) for the French VT I missile.[17] The exit cone of this missile experiences a large temperature gradient because of the 5,000 °F plume that blasts through it. This structure is supposed to last for 3 seconds, but thermo-mechanical loads can be a problem. As illustrated on p. C-22, designers rely very heavily on the use of FEM and stress analysis. Dr. Ho observed, however, that the FEM is only as good as the assumptions. If one makes the wrong assumptions, the model is wrong. Clearly, test data are needed to supplement these studies. Unfortunately, however, these data are not usually available in the design phase. The figure on p. C-23 illustrates the effect of temperature distribution on the material profile (virgin material, char area, and eroded area) in this motor case. Another example of materials selection for various high-performance missile components was given (p. C-24). Several of the identified materials are used for their high-temperature performance capabilities.

Dr. Ho concluded with a discussion of the need for high-temperature composite materials. This need is attributed to the hostile operational environment for the missiles and the fact that increased performance leads to higher operating temperatures. Increased efficiencies at such temperatures are an additional benefit. High strength and stiffness are also required to meet the severe flight loads. LtCol Obal inquired about cost, noticeably absent from the wish list. Dr. Ho replied that "if you don't have performance, you don't have a missile."

C. LOCKHEED MARTIN ELECTRONICS & MISSILES, LES KRAMER

Dr. Les Kramer provided an overview of current uses of composites and closed mold manufacturing technology for missile applications at LM (p. C-27). This division of

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15 The back-up is quartz-reinforced poly-imide.

16 According to Dr. Ho, the cost is expected to be $20 million less than the projected cost of the baseline system.

17 This missile was the first tactical missile with a somewhat large composite structure.

LM makes small and large tactical missiles. According to Dr. Kramer, these types of missiles are usually made in higher volumes, as many as 100,000. He also noted that the use of composites in these missiles is "built in from the early design stages." Features driving the selection of materials include properties and service environment as well as component cost, which is highly dependent on the fabrication method. Composites are advantageous because they can be designed for easy assembly. The bar chart on p. C-29 compares specific properties of common aerospace materials with those of injection molded thermoplastic composites (TPCs) and continuous fiber-reinforced thermoplastics. The TPCs compare very favorably with the other materials. The aerothermal environments may be above or below Mach 1 depending on the mission requirements. Dr. Kramer noted that no missiles with speeds > Mach 1 have been made using composites. In response to a question from LtCol Obal, Dr. Kramer indicated that Martin Marietta originally used metals exclusively for missiles. Switching to composites has been difficult. For new designs, composites are considered from the start, particularly since experience shows that the "black aluminum design approach doesn't work." Dr. Kramer then observed that there is little motivation to insert composites in block upgrades. It would have to be a performance requirement. It would not be done for cost or weight reasons.[18]

The graph on page C-30 illustrates the relative costs of various composite fabrication methods. Filament winding, thermoforming (TPCs only), pultrusion, Resin Transfer Molding (RTM), and injection molding (IM) are less than one-third of the costs of the hand lay-up process for TPCs (relative value of 1.0), a fact that makes the closed mold methods attractive for missile applications. Jerry Sundsrud (3M) inquired about the hand lay-up process. Dr. Kramer replied that prepreg was laid up by hand and then autoclave cured for the baseline. In response to another question, Dr. Kramer noted that there is some hand labor in RTM and some of the other lower cost processes, perhaps less in IM. LtCol Obal asked if there are any missile components that would be scrapped because they would be too expensive to repair. Dr. Kramer thought there probably were, although most parts would be repaired. LtCol Obal then mentioned the move toward the smart materials concepts, i.e., those structures that have health monitoring capabilities, for example. Dr. Kramer said that problems occurred when interleaving of titanium in a composite part was attempted. A typical metal structure fabrication sequence, shown on p. C-31, may involve turning, drilling, fastener installation, and so forth. The fabrication sequence for the TPC may be considerably simpler (p. C-32), in addition to providing reduced weight

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18 They consider what they make to be wooden rounds.

and greater structural efficiency at lower cost. It is possible to combine discontinuous TPCs with continuous fiber-reinforced TPCs to make a missile fin, for example (p. C-33).

Dr. Kramer discussed IM[19] relative to aluminum investment casting for a generic missile wing structure (p. C-35).[20] The aluminum casting process involves 15 steps while the composite IM process involves only 7 steps. In comparing the process costs with respect to properties (p. C-36), injection molded Poly-Ether-Ether-Ketone (PEEK), investment cast aluminum, and precision forged aluminum all meet the material property requirements, but the injection molded part is the lowest cost. The IM process can be optimized by the use of long, discontinuous fiber reinforcements to achieve room temperature strength in the molded part greater than that of the cast aluminum baseline (p. C-37).

The Javelin program has been successful in demonstrating the utility of closed mold manufacturing processes (p. C-38). IM has been used to make wings and fins, internal bulkheads, guide vane supports, a battery cooling unit/pylon on the launch tube, and numerous secondary structural components such as circuit card supports and electrical supports (see p. C-43). The MMNM process was used to make the warhead airframe and support cone and the guidance electronics unit airframe, both from graphite/epoxy composites. The portable Javelin system is described on pp. C-39–C-41. The main elements are the round and the Command Launch Unit (CLU). This anti-tank system weighs less than 50 pounds. The "wooden" round is supposed to have a 10-year shelf life. The launch tube assembly is a rugged design constructed with composites. Launch tubes are disposable. The missile has a long wavelength infrared (IR) seeker, a robust target tracker, a tandem warhead, and a soft launch feature with a minimum signature. The CLU is rugged and lightweight and has a very reliable design; the thermal sight system can operate for 4 hours (battery limitation). Dr. Richard Parnas [National Institute of Standards and Technology (NIST)] inquired about the manufacturing rates. Dr. Kramer indicated the IM is much faster because of very low cycle times. Dr. Parnas also inquired about inspection of such molded parts. The parts are inspected visually and measured for dimensional tolerances. IR thermography is used for some parts. LtCol Obal posed a question about disposal: assume 10,000 components are manufactured now and 5 years later a decision is made to dispose of them. How would disposal be accomplished?

19 IM of composites is limited to discontinuous reinforcements.

20 It is important that the composite material show equivalent performance and lower cost to compete with aluminum investment casting.

Dr. Kramer responded that thermoplastic composites are more easily disposed of. The material can be chopped and reused in commercial products. He further noted that the fiber has value if the resin can be removed. It can also be recycled into commercial products. End of life disposal has not really been considered. One of the attendees commented that industry should take the lead and be proactive in determining how to do this; otherwise, the government will impose its own set of typically burdensome regulations. Dr. Parnas remarked that the automotive industry is moving toward thermoplastic materials. Billions of pounds per year usage rates are expected. Thermosets are considered a long-term liability by this industry, although there is some effort to develop resins that can be depolymerized. Dr. Parnas emphasized that companies should "do it before the EPA [Environmental Protection Agency] jumps down your throat." Dr. Kramer concluded this part of his presentation by making a few comments on composite manufacturing lessons learned during the Javelin program (p. C-42). One observation he made was the significant amount of hand labor—cutting and placement of prepreg—for MMNM process. While complex shapes could be fabricated with net shape wing slots, wrinkles and porosity were problems. Issues associated with the IM process included gates for fiber alignment, tolerance control, and fiber survival in the auger (part of the injection system).

RTM and injection molding processes have also been used to make components for the Longbow missile (pp. C-44–C-45). An adsorptive composite missile radome,[21] illustrated on pp. C-46–C-48, was fabricated using a closed mold process. This radome, a high precision part, is currently not made in a single processing step although improvements have been made. A composite reflector/antenna dish also was fabricated (p. C-49). The fire control radar (FCR) mast-mounted assembly was 31 percent composites (p. C-50). Composite components consisted of the aft dome, the baseplate, radio frequency interference (RFI) brackets, an antenna bracket, a transmitter bracket, and a radome, all made by IM. RTM is being considered for the hub assembly. Page C-51 shows the fabrication/assembly process for these components, and page C-52 shows the structure certification program, from materials to full-scale assembly. For example, the full-scale assembly was tested through static tests, a vibration survey, and an icing test.

The final segment of Dr. Kramer's presentation addressed three R's (p. C-53): rapid prototyping, RTM simulation, and recycling. Rapid prototyping is of interest because tooling can be directly generated and fit check can be easily and quickly evaluated.

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21 The composite structure contains electromagnetic interference (EMI) shielding.

LM is investigating a stereolithography process, noting that the equipment utilization rate is 85 percent. The machine is large. Components as large as 20 in. × 20 in. × 23 in. can be made (pp. C-55–C-57). He described the process and potential benefits (p. C-58). For example, cycle time is reduced from 1 to 3 weeks to 24 hours, and more design iterations can be run in the same time period (from 1 to 2 to 3 to 5). Dr. Kramer thought the precision was good, although the amount of cure is not perfect and some other issues require consideration. In response to a question, he reiterated that doing a negative of a structure to get a mold is possible. Tom Anderson indicated that laser sintering was being used in his LM group and that several other rapid prototyping processes are available.

Dr. Kramer noted that LM was "being dragged into the RTM arena kicking and screaming." To address issues of inadequate part quality, lack of part-to-part reproducibility, and a trial-and-error approach to tooling and preform design and process development, LM-Orlando is developing an RTM simulation model. The RTM simulation program runs on a 486 personal computer (PC). It addresses nonlinear, complex relationships between processing variables and process performance for many resin and fiber combinations using a cascade correlation algorithm (p. C-60). The graphic on page C-61 is an example of the part filling process. Vent openings, resin viscosity, and weave porosity are all considered in the model. Neural nets are currently being used to design the system rather than as a process control mechanism, the ultimate goal. The graphic on page C-62 illustrates the process control scheme. Signals from optical fibers are processed through a performance classification network to determine the degree of cure. This result is then compared to a target value, and a quality comparator network determines the temperature change necessary to improve the degree of cure. A comparison of actual and predicted percent monomer shows good agreement (p. C-63).

The third R is recycling (see cartoon on p. C-64). LM has been working on recycling AS4/APC-2 thermoplastic composites. For aircraft applications the scrap rate is typically on the order of 30 percent. The table on p. C-65 shows the degradation in tensile strength and flexural modulus that occurs when unidirectional tape prepreg material is chopped and compression- or injection-molded.

Dr. Kramer concluded with a statement that LM has been using composites in secondary structures for missile systems for approximately 20 years. Most of these components have been injection-molded. Composites have only been used in primary structures within the last 5 years. Because of typically low missile acquisition costs, closed mold manufacturing processes are necessary. IM and MMNM have been most successful

in helping LM achieve their cost goals and customer requirements. With the availability of a simulation tool, using RTM to manufacture composite missile components is expected to increase. LtCol Obal asked about the effect of the Javelin program on composite use in LM-Orlando missile systems. Dr. Kramer replied that the Javelin program was a test case for the company. If it is successful, he anticipates increased use of composites, depending, of course, on the particular missile system requirements. Dr. Ho from LV indicated that IM is being considered in the development of the Predator missile system.

D. HUGHES MISSILE SYSTEMS, ROSS RINGWALD

Mr. Ringwald addressed a number of topics (p. C-68), including concerns about composites, program office vision, properties of interest, potential applications, suggested focus areas, and materials test data. He took the unusual approach of asking his chief engineers at Hughes why advanced polymer composites were not used more frequently in their missile systems (p. C-69). One of the primary issues associated with composites concerns its ability, if used, to meet the development schedules. This concern is attributed to a lack of understanding of the material and its interactions with the rest of the system and is also tied closely to the ability of composite components to pass qualification tests. Other issues include consistency in quality and strength, high-temperature performance above 800 °F, compatibility with fuels and other fluids (as for aircraft), damage tolerance and reparability, and joining and load transfer at joints (especially with respect to bolt holes and bonding). The chief engineers recognized that black aluminum designs are not realistic. Direct substitution of composites for aluminum works, but it is not the most efficient use of composites. By combining parts (part count reduction), it may be possible to give the missile some extra performance benefit.

The vision of program offices on use of composites was highlighted next. Mr. Ringwald indicated that the program offices would like to use more composites. They are generally optimistic about use of composites and believe in the performance advantages (e.g., strength-to-weight and stealth), but they do have concerns, mostly about cost (p. C-70). There is an understanding that the system can be tailored to customer specifications by using composite materials and that useful service life can be improved. Cost reductions are thought to be achievable through part count reduction to reduce assembly time and integration of other features and/or functions into the composites ("make the structure do more things"). Associated with these options are continuing cost reductions, i.e., reducing process costs ("make the structure do more for less"). If

composites are to be used, Mr. Ringwald indicated that the schedule must be realistic and risk mitigation activities, typically in the form of a metal part, should be addressed.

Page C-71 highlights specific properties of interest. For example, time-at-temperature requirements include 6 hours of carry between –65 to +180 °F, 3 to 4 hours at +400 °F, and 2 minutes at +1,000 °F. Mr. Ringwald noted that composite bonds require a 100 percent proof test and that knockdown factors are used for hot/wet performance.

Mr. Ringwald observed that almost everything on a missile can be made with composites, as illustrated on p. C-72. Examples include inlet ducts, radome/nose cone, fuselage, bulkheads, and control fins, among others. Processes of interest for making such components are compression molding, RTM, and hand lay-up. Hughes has a composite laboratory in their factory. He commented that the company has made only bolt-on composite components so far. When asked why, Mr. Ringwald replied that there is "a concern that it can't be made." He observed that an integrated product team (IPT) approach in which everyone works together is required for successful implementation. LtCol Obal remarked that maybe missiles should be built for planned obsolescence—build them to survive 4 to 5 years and then throw them away. Mr. Ringwald replied that perhaps that would be a good idea, but current program requirements still ask for long life.

Suggested focus areas for composites (p. C-73) mentioned by Mr. Ringwald include agile/low rate manufacturing especially addressing versatile tooling and specific processes, and a maintenance design that considers hybrid materials and development of repair systems and methods. He remarked further on high tooling costs, noting that Hughes "must be faster coming on-line." They must be "more versatile," low cost, and able to build and assemble systems more quickly. A continuing need for data, specifically stiffness, strength, thermal, and electrical properties, also was identified.

Availability of standardized test data was identified as a key issue preventing use of composites (p. C-74). Mr. Ringwald remarked that a significant amount of data has been collected over the years but most of "it wasn't collected in the right manner." The availability of standardized data would increase confidence in the materials. Material and design data would be more easily shared if standardized test types and methods were used. As an example, he mentioned the Big Three Automotive Composites Consortium, which is working to develop a database containing comparable design information for automotive structural analysis. The consortium is also developing test methods and a durability information base.

Mr. Ringwald concluded by stating that, with proper design, he did believe low cost could be achieved for composites. Generally, there is confidence that composites can meet requirements for applications in which high strength and stiffness and low weight are important. Technical concerns stem from uncertain environmental effects, integration of composites with other components, and the ability to meet program schedules. For composites to be cost-competitive with baseline metal components, lower cost/low rate production process approaches must be developed. To that end, Hughes is beginning to consider the RTM process as one alternative. The need for methods to integrate other features and functions in the composites also was identified. Common test data seem to be a critical factor leading to the increased use of composites. Mr. Ringwald commented that "analysis people will believe the analysis" with good data. One of the other attendees observed that the problem of data collection must be bounded.

E. McDONNELL DOUGLAS AEROSPACE (MDA), JERRY LEHMAN

MDA is currently involved in two missile programs: Tomahawk and Harpoon/ SLAM (p. C-77). The company also has been participating in several other programs that are considering low cost composite missile structures and RTM processes (p. C-78).[22] MDA worked on tooling technology for electronics enclosures in the RTM program with the Great Lakes Composites Consortium (GLCC). Outer wing leading edge seals, manufactured via RTM, have been implemented on the F/A-18E/F. Design allowables and material and process specifications were developed on this project.

The purpose of the Low Cost Composite Weapons (LCCW) program was to develop a broad technology base in low cost weapon construction (p. C-79). The air-carried, flat-bottomed missile consisted of eight major components. The idea behind the program was to use composites to make every component. Since composite materials were selected up front, MDA wanted to see if low cost could be obtained. Activities included technical evaluation; design and fabrication of tooling; fabrication, assembly, and testing of the structure; determination of production costs; and development of design guidelines. Several composite manufacturing processes were selected for study: RTM, pultrusion, compression molding, diaphragm forming, stamping, roll forming, ply stacking, and IM. Both thermoset and thermoplastic composites were considered. Assembly approaches and in-process control techniques also were evaluated. In the final analysis, RTM turned out to

22 MDA has also spent internal research and development (IRAD) funds on development of composites manufacturing methods.

be "a star player." As shown on p. C-80, it was used for the bulkhead, nose, dispenser tube, fin, and strongback as well as for the joining demonstration.[23] In response to a question, Mr. Lehman indicated that the program considered all of the parameter space; however, there was a strong focus on cost.

The next segment of Mr. Lehman's presentation addressed the "how to" or process of selecting composite materials and manufacturing processes. He emphasized the importance of a team approach, including material and part suppliers and the customer, for successful implementation. Tools necessary to achieve implementation could include design for manufacturing and assembly/disassembly approaches, rapid prototyping, quality function deployment (QFD), and so forth. Customer needs—cost, weight, various "-ilities"—also must be factored into the material selection, which is part of QFD. For example, MDA would not make the strongback using IM because the part would not be strong enough. Size and shape of the component might be other customer considerations. Mr. Lehman indicated that it is possible to assign weighting factors to each of the customer needs even though these needs may not be known exactly. As an aside, he commented that one should not get hung up on databases or the lack thereof. MDA performs "quick-look" tests for feasibility, followed by developmental tests and creation of B-allowables. He also mentioned that the customer will say when enough is enough with respect to data, noting that designers do not really need that much data since critical properties are often identified through analysis.

The flow chart on page C-81 illustrates overall process for screening composite manufacturing approaches. Knowing the factors of importance to the customer, the component geometry, and service temperature one can limit the following:

- Matrix materials with respect to service temperature
- Processes with respect to matrix
- Processes with respect to component function
- Processes with respect to component geometry
- Materials and processes with respect to factors important to the customer.

At this point, material and process candidates can be screened and components can be sized. The table on page C-82 lists the thermoset and thermoplastic matrix material options. Most air-to-ground missiles operate in a temperature range acceptable for epoxy

23 The bulkhead, nose, fin, strongback, and joining demonstration also were made by stamping, diaphragm forming, ply stacking, compression molding, and pultrusion, respectively.

matrix materials while air-to-air missiles require higher temperature matrix materials such as bismaleimides (BMIs), polyimides (PIs), or polybenzimidazole (PBI). Higher temperature materials typically imply increasing part costs. The table on page C-83 shows the suitability of particular manufacturing processes for possible matrix materials. In this table, processes are marked as production-ready (e.g., RTM for epoxies[24]), needing scale-up (pultrusion for epoxies) or development [filament winding for poly-phenylene sulfide (PPS)], or high risk [pultrusion of poly-aryl-ether-sulfone (PAES)]. Limiting processes because of component function relies heavily on past experience with composites for airframe applications. Designers learn by talking to suppliers and making parts on their own. The philosophy is to use the minimum amount of materials and processes for a system, the objective being to use a single process for as many parts as possible. RTM is an example of a process that is useful across a wide range of missile components, as shown on p. C-84. Jerry Lehman envisioned a table like this as "a living table" that would fluctuate from year to year. The fourth step limits the process because of component geometry, a major objective being to reduce the number of parts. The example on p. C-85 is for a missile fin. Geometry features of interest include a one-piece, co-cured part with root fitting and core; a multi-piece construction such as an integrally stiffened structure with ribs and bonded fittings; variable skin thicknesses; and net-molded leading and trailing edges. The final step addresses factors important to the customer. Important characteristics might include cost, process cycle time, cure and consolidation temperatures, moisture absorption, and service temperature, among others. In the table on page C-86, these features (with a weighting factor) are rated from best to worst for the different matrix materials. Mr. Lehman observed that not every process works for every component. In response to a question, Mr. Lehman indicated that most of the composite manufacturing would be sub-contracted out-of-house. He also mentioned that one problem with doing such work in house is that a company may develop a favorite process that may not be the best/most appropriate one, and, in the long run, the company loses money.

For cost issues Mr. Lehman presented tables comparing fiber cost and performance and process costs for material, expendable material, labor and initial tooling. Fiber performance characteristics, evaluated from a best to worst case, include approximate roving cost, tensile and compressive strength, tensile modulus, fiber toughness, dielectric constant, dissipation factor, density, material compatibility, ultraviolet (UV) stability, and

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24 This is especially true in commercial production applications. Further development may be necessary for transition to aerospace applications.

temperature resistance (p. C-87). The table on page C-88 conpares cost versus process. The processes are listed in order of generally increasing total production cost, from IM (lowest) to thermoplastic hand lay-up/autoclave processing (highest). RTM is somewhere near the middle.

Mr. Lehman concluded by stating that composite missile parts have been demonstrated and that one can choose from several composite processes. Process selection depends, in large part, on the service temperature and geometry of the component and the required production rate. RTM is advantageous because structurally efficient laminates and near net-shapes can be produced. RTM also offers the potential for part count reduction. Dr. Janet Sater inquired about the material and process selection approach that would be involved in a clean sheet missile design that would include both metals and composites. Mr. Lehman replied that the approach would be similar. In response to a question from Gary Wonacott, the speaker indicated that he thought everything except the strongback and the bulkheads would be made using composites. Mr. Lehman emphasized, however, that the decision on whether to use composites depends on the size, shape, and loading of the structure.[25]

F. RAYTHEON CORPORATION, WILLIAM FOSSEY, JR.

Bill Fossey stated up front that use of composites in current Raytheon systems is limited. More recent programs have been opened to the increased use of composites, but there are several limitations (p. C-91): designer lack of experience; lack of missile-specific design data, especially in the high temperature regime; and cost and schedule constraints.[26] The graphic on page C-92 illustrates current applications on Raytheon missiles. These applications include, among others, radomes and radome mounting rings,[27] thermal insulation, motor casings, and strakes. Most of the insulation applications are nonstructural. Applications in next generation systems (p. C-93) could include internal structural components such as electronic frames and support structures, bulkheads and seeker mounts, and fuselage structure, wings, and fins.

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25 At this point in the workshop Mr. Lehman presented the composite part fabricator perspective (RTM), which will be described in Section IV.A.

26 Mr. Fossey amplified this point by stating that schedules are faster, system acquisition costs are lower, and buys are smaller.

27 Composites are used to match thermal expansion and take loads.

This segment of the presentation focused on design requirements. Missile designers at Raytheon consider three environments in the design of missiles (p. C-94): storage (–160 °F to +150 °F, unregulated humidity), captive carry/deployment (part of the operational environment), and high-speed flight. Mr. Fossey emphasized the fact that available, common databases do not address the flight regime very well, particularly short-term, high-temperature data. He noted that Raytheon has its own proprietary database, which it is not inclined to share. Other concerns include the large number of specialized environmental conditions that must be considered and the fact that high thermal gradients exist through the structure. Since every missile flight is different, developing standard tests is difficult. Designers end up guessing how far they can push the material. Additional, more detailed analyses are desired. Modeling during transient conditions is especially critical but difficult to do. Specialized qualification testing is required (p. C-95). This testing will include specimen-level testing using quartz lamps, for example; elevated temperature static and dynamic structural testing; hot flow tests; and hot wind tunnel tests. Mr. Fossey indicated that the cost for an elevated temperature coupon test is about $500 vs. about $50–$100 for a standard test. Hot flow and wind tunnel tests, performed at China Lake, also are expensive. He also stated that the Raytheon designers live with guesses and analyses until they end up with a few relevant, specific conditions, noting that "racial memory plays a big part in design." In addition, they usually "end up with considerable factors of safety." Mr. Fossey mentioned that the Sparrow missile, for which an experimental composite control fin was developed, experiences a leading edge temperature of about 800 °F. This part experienced large thermal gradients and, apparently, suffered somewhat from extreme erosion. A final design requirement mandates that the missile must be compatible with existing launch hardware. This is a volume constraint.

A number of operational issues must be addressed. Thermal management (p. C-96) must be addressed for flight conditions (typically short duration) and captive carry/test (typically long duration). Approaches include heat spreaders and metallic inserts for flight conditions and active cooling for the captive carry/test. The high fatigue environment affects the performance of bearings and influences bearing loads, an important attachment issue (p. C-96). Mounting rings and secondary inserts are a third concern (p. C-97). Raytheon designers typically get around interface issues by using mounting rings, but a weight penalty and cost is associated with them. The bondline is a potential problem with respect to possible localized heating. Pull-out strength is a possible issue for secondary inserts. Ground is important for the electronics as well as for EMI/RFI protection (p. C-98). Static charges are a special concern in the factory and around explosives. Since most

missiles are designed as a 10-year wooden round, water penetration is not desirable (p. C-98). Seals are very important, too, especially against metallic components that may expand and contract with temperature changes (p. C-99). Stresses in electronic substrates caused by thermal expansion differences also must be addressed. Damage tolerance is another important issue (p. C-99). Mr. Fossey noted that any kind of defect can be introduced on the factory floor long before it would occur on the field. This damage occurs primarily during secondary operations, which imply extra handling of the missile on the factory floor.

Design and prototype lead times are two important production issues (p. C-100) Since the design resource pool is small and few people in this pool have relevant composites experience, more extensive analyses and much more experimental testing are performed. Additional analysis and testing implies higher costs. At the current time Raytheon uses multiple, outside vendors; however, Mr. Fossey noted they would like to rely on a single vendor. Typical prototype lead times are 3 months. The lead time for composites is considerably longer, e.g., material lead time can be on the order of 12 weeks (or more), depending on the specific material. These lead times combined with the tool lead time and the (probably) required process development, make it difficult to fit composites into a rapid turn-around program. Process control and NDI are also very critical production issues (p. C-101). Raytheon engineers have significant input into process control. Documenting material and process specifications and statistical process control procedures is particularly important. For NDI, receiving tests are performed up front to get the bad material out of the manufacturing process as early as possible. For example, materials are 100 percent inspected by X-rays and ultrasonic testing. Mr. Fossey mentioned that some of the 100-percent inspection receiving tests are conducted in house at Raytheon. Other materials are only spot-checked. Cost usually drives the amount of inspection. Standard test methods are required and must typically be developed to be cost-effective. Mr. Fossey indicated that missiles are typically purchased in small to medium lot sizes (p. C-102). A typical one-year buy might be 700 missiles.[28] To make this many missiles requires that material be purchased and stored, and this requirement presents a potential problem for some composite materials. Raytheon's view is that a significant

[28] Mr. Fossey observed that using composites requires a dramatic performance improvement and/or potential for low cost relative to a baseline (usually metal). He believed that composites would probably only be used on a new program/system, not an existing one. The question comes down to the following: What is the value of composites to the customer? For the PATRIOT missile, weight reduction that leads to range improvement could be advantageous.

amount of "raw" composite material would end up being discarded. On the other hand, buying material in relatively small incremental quantities usually means the cost is higher. The difficulty associated with amortization of tooling also was mentioned. The plant environment is a source of several production-related issues (p. C-102). A high number of assembly/disassembly cycles is typical for Raytheon in missile manufacturing, and these procedures can result in increased damage to the structure. This practice leads to reparability issues, the primary concerns being subsurface defects and their effect on performance. Raytheon uses Beech Starship data as a starting point, although it is, in part, a handling and education problem.

Mr. Fossey concluded by summarizing the need for reduced weight, increased performance, stringent signature requirements, and cost-effectiveness in new systems. The speaker noted that the government, users, and supplier community must work together to achieve common goals, and he recognized the need to expand application of composite materials. He emphasized that "affordability is key."

G. ROCKWELL AEROSPACE/ROCKETDYNE, RICHARD HILSCHER

The Rocketdyne Division has built all the Kinetic Energy Weapons (KEW) kill vehicles (KVs) and KV propulsion systems for Rockwell (p. C-106). Ongoing KEW programs at Rocketdyne include THAAD, Anti-SATellite (ASAT), Development of Advanced Risk Reduction Technologies/Lightweight Exo-Atmospheric Projectile (DARRT/ LEAP), Exo-atmospheric Kill Vehicle (EKV), and Navy Theater Missile Defense (TMD). The speaker, Mr. Rick Hilscher, has been involved with the THAAD program.

Rocketdyne is interested in applying composites technology if it is mature enough. The company has some experience with composite missile structures as shown on page C-107: internal structures in the SpAce-Based InterceptoR Flight Experiment (SABIR FE), Advanced Hover Interceptor Test (AHIT) vehicle, ASAT and LEAP kill vehicles, and the EKV as well as outer shells of the KKV Hover Interceptor Test (KHIT) vehicle and THAAD DACS. Most of the structures are a mix of composites and machined aluminum. The photographs on pages C-108 and C-109 illustrate these systems. THAAD is considered the first system that will go into full production.[29] Mr. Hilscher indicated that the bulk of Rocketdyne's experience base is with machined aluminum and AlBeMet, an aluminum-beryllium alloy. For example, an AlBeMet alloy has been used on the LEAP

[29] Mr. Hilscher observed that now is a prime opportunity to insert composites because EMD is 1 to 1.5 years away.

(p. C-109) and ASAT kill vehicles. Technical concerns related to composites include heat transfer (a number one issue); integrated mounting flanges; materials compatibility (load transfer, thermal expansion, bearing surfaces, and so forth); long-term storage requirements; manufacturing tolerances; and testing (p. C-110). LtCol Obal observed that heat transfer was also a problem for spacecraft and mentioned Amoco's high thermal conductivity carbon fiber, K1100. For Rocketdyne, the advantages associated with use of composites are not critical to system performance. Mr. Hilscher believed additional programs and funds would be required to incorporate composites into production systems.

Most structural parts that have been made recently—such as the THAAD DACS and EKV bulkheads, the EKV primary and separation system structure, and the THAAD DACS divert and Attitude Control System (ACS) manifolds (pp. C-111–C-112)—are quite complicated, with challenging tolerances and geometries. Requirements for a program focused on producible composite structure bulkheads for THAAD DACS propulsion included, among others, reducing component weight by 20 to 50 percent while maintaining or exceeding stiffness and strength relative to the aluminum baseline at reduced per unit production costs (p. C-113). The steps in this program were to identify candidate components; design and fabricate prototypes; conduct ground tests;[30] and perform manufacturing analyses to assess key issues and projected production costs over a period of 3 years. In this program, SPARTA fabricated a THAAD aft divert bulkhead (p. C-114) with financial support from the Army Research Laboratory (ARL). The IM7-reinforced composite component was 30 percent lower in weight and exceeded the strength and stiffness requirements (relative to a machined 7075-T73 Al baseline) for approximately half the *production* cost.

Key testing and analysis requirements must be met before composites will be considered. These include material level data such as supplier coupon test data and material property data; component level tests dealing with environments, critical loading conditions, modal tests, non-destructive and destructive tests, and combined loading/environment tests; and system level tests such as static hot firing, hover tests, separation tests, and flight tests (p. C-115). Composite material evaluation criteria shown on page C-116 are taken directly from THAAD specifications and include general material properties (the standard properties such as strength, stiffness, fatigue, and so forth), environmental effects such as temperature, humidity, and vacuum conditions; and data obtained through prior experience and/or

[30] LtCol Obal indicated that he was investigating several funding sources for performing ground tests of the part.

specifically designed test programs. Subelement testing is also important (p. C-117). Such test specimens could simulate critical areas and approximate lay-ups of specific geometries, fillets, or fastener locations. Tests would involve critical loading and environments, especially shock and vibration. The specimens would be post-test inspected using ultrasonics, X-rays, and destructive methods to search for undesirable features like delamination, cracking, and voids.

Mr. Hilscher identified a number of components that lend themselves to closed mold manufacturing with composites (p. C-118): bulkheads, aeroshells, primary structure (for exoatmospheric vehicles), and secondary structures.[31] Other possibilities include structural manifolds[32] and thrust chambers. Allan Samuel inquired about cost and weight, which are of concern for these components. Technical challenges for closed mold manufactured components are numerous: tolerances; geometric complexity; shock and vibration performance; thermal environments; assembly processes; life cycle and long-term storage; and propellant compatibility. Specific values are given on p. C-119. For example, there are 300+ dimensions on the divert manifold that are important and must be measured, although Mr. Hilscher said the part would be designed differently with composites. The table on page C-120 shows the anticipated quantities of bulkheads and manifolds for the next 10 years over a range of lot sizes. The bulk of these components would not be needed until the 6- to 10-year time frame.

One of the primary conclusions was that more data are required to fully evaluate composites for machined, cast, and forged metal structures. Flexible manufacturing processes are attractive but demand closer interaction between designers and fabricators. Costs associated with the increased use of composites are significant and would include design database development, manufacturing process integration, resolution of technical issues, and increased user experience and confidence. Mr. Hilscher further observed that designers typically do not think of composites as an option. Key unknowns are the cost of closed mold composite components relative to cast, finish-machined components and achievement of the necessary tolerances. He stated that aluminum castings can meet the performance requirements; however, Tom Anderson noted that the follow-on/EMD program has some severe design-to-cost requirements.

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31 Mr. Hilscher mentioned the possibility of incorporating these secondary structures into the rest of the missile structure (part count reduction).

32 These components are quite complicated, with asymmetric internal passages. The current component is rough machined and e-beam welded.

III. MATERIAL SUPPLIERS

A. PREFORM TECHNOLOGY, FIBER MATERIALS, INC. (FMI), PAUL MARTIN

FMI is heavily involved in the research, fabrication, testing, and evaluation of advanced composite materials. The company has special expertise in weaving, particularly with multi-directional or N-D (N-dimensional where N is any number) reinforcment methods. This weaving technology is important in manufacturing complex preforms for closed molding or other composite processes. In response to a question, Mr. Martin indicated these preforms can be woven "with a high degree of reproducibility."

Mr. Martin began by describing fibers that can be "woven," the type of weaving that can be done, and the relevant preform processes (p. D-3). Classes of fibers range from glasses to ceramics to metals. In response to a question about high modulus graphite fibers, Mr. Martin indicated that the ability to be handled is an issue. Fraying is observed. A sizing applied to the graphite fiber can alleviate some of the difficulty, but the sizing must be compatible with post-weaving process steps. Possible weave constructions include one-directional, two-directional, multi-directional, and specialized hybrid adaptations of these constructions. A range of processes can be used, but not all constructions are suitable for every process. For example, a two-directional weave construction is used in making braided preforms, cloth, or tape, while a one-directional "weave" is useful in filament winding or unidirectional tape. Page D-4 shows illustrations of several weave constructions. The complexity of the N-D constructions is obvious. The 3-D cartesian form is used in block weaving, and the 3-D polar weave is used for cylindrical parts.

The range of characteristics achievable in a preform through N-D weaving also were identified (p. D-5). Typically, one would like to begin with the overall configuration of the part to determine its suitability for weaving. Dimensions include 0.25 inches (inner diameter) to 85 inches (outer diameter) by 60 inches high. The thickness ranges from 0.15 to 10 inches. According to Mr. Martin, the weave can be tailored by location and direction[1]

[1] In essence, fiber can be placed where desired, within some limitations.

for a variety of shapes including blocks, cylinders, cones, flanges, contoured shapes, and so forth. Additional information was presented regarding design parameters for various weave types (p. D-6). For example, bundle-to-bundle spacing can range from 0.015 inches to ≥ 0.125 inches. This spacing depends somewhat on the size of the fiber. Mr. Martin noted that the smallest size yarn currently available is a 1k carbon fiber tow. The achievable volume percent in each direction can range from a minimum of 5 to 10 percent to a maximum of approximately 70 percent although the overall preform fiber volume percent ranges from < 35 to 55 percent.[2,3] And, of course, reinforcement orientation can vary from a standard 3-D or 4-D, for example, to the hybrids such as 2-D/3-D or 3-D/5-D combinations. In response to a question regarding other sources for woven products, Mr. Martin mentioned that one French company has the capability to perform 2.5-D weaving. Another French company manufactures Noveltex, which is a pseudo-3-D weave.

The N-D weaving process (p. D-7) has several advantages, one of which is its suitability for automation. This adaptable process is believed to offer excellent design flexibility in terms of directional fiber loading, hybrid fiber capability, and graded structures. Near net shape preform configurations also can be woven. By varying the fiber volume fractions in particular directions, composite properties (i.e., mechanical properties, thermal characteristics, ablative performance, and mechanical wear) can be tailored. Mr. Martin did note that the discrete fiber locations in weaving caused cubical shaped voids that cannot be filled with fiber reinforcements.

Several approaches can be used in manufacturing N-D preforms for closed mold processes (p. D-8). Types of equipment used in weaving include a modified textile loom, a manual loom,[4] or a stitching machine. Multi-directional woven products from textile looms may be in the form of a thick broadcloth fabric or narrow tape. Possible construction features include a collapsible weave (e.g., warp interlock), a compressible weave (e.g., angle interlock), and tailored void paths. The sketches on page D-9 illustrate weave construction possibilities and include a 3-D orthogonal,[5] angle interlock, warp interlock,[6]

2 The ability to be handled is a particular problem for the low volume fractions since the preform is very loose and is not self-supporting. The primary reason for using this loose preform is resin flow.

3 According to Mr. Martin, a fiber volume percent of 40 to 50 percent is typical. He also mentioned that obtaining a fiber volume fraction greater than about 55 percent is theoretically impossible although he thought it may be possible to achieve something larger by using a compressible preform.

4 Net shape preforms are usually made using the manual loom.

5 This type of preform weave may experience fiber buckling during closed mold manufacturing.

and stitching. Page D-10 shows the details of the 3-D bias and 4-D nonorthogonal weave configurations. The 3-D bias weave has six layers, and the 4-D weave has seven layers.

Mr. Martin next described the quality control aspects of N-D weaving (p. D-11). Receiving inspection activities include yarn certification and inspection of weave tooling. The loom set-up is examined as part of the in-process inspection. Also, every layer and row of the woven preform is visually examined during weaving. Included in the relevant shop floor paperwork are an R&D traveler, a Standard Operating Procedure (SOP), and an In Process inspection Operation Schedule (IPOS), depending on the program or customer requirements. The final preform undergoes physical measurements, a check on bulk density, and X-ray radiography[7] before being shipped or used in the fabrication of a composite component.[8] Mr. Martin stated that the customer usually defines the required quality in terms of some number of allowable missing or displaced sites per unit area: 5 sites/in^2 is typical. In finer weaves containing, for example, 1,000 sites/in^2, FMI may be allowed 50 missing/displaced sites.

Mr. Martin concluded by noting that N-D weaving is a demonstrated process although it has not been explored in detail for use in closed mold manufacturing. So far only coupons and subscale components have been evaluated. He also indicated that there is a lack of property data for these types of weaves and that this problem is exacerbated by the wide range of fiber orientations and volume fractions that can be achieved. Effects of the molding operation on the weave reinforcements also need to be fully characterized.

Several questions were raised during the final discussion. Dr. Parnas inquired about the pressure required for fluid flow in the various weave types. Mr. Martin replied that 500 pounds per square inch (psi) is adequate for the compressible or collapsible weave types but mentioned that each weave architecture will have different pressure requirements. In response to a question about equipment, Mr. Martin responded that FMI purchases textile looms and makes special modifications to enable the machines to handle additional reinforcing fibers.

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6 The angle of the fibers in this product form become larger (e.g., change from 90° to 120°) during manufacturing because of preform collapse. This fabric is expected to elongate at the ends, which presents a potential problem during closed mold manufacturing. So far, FMI has investigated this phenomenon only at the coupon level.

7 The X-rays will pick up missing sites, misplaced sites, or double sites.

8 FMI makes C/C composites using a multi-step, high-pressure liquid impregnation process. Mr. Martin mentioned that there may be more of a limitation in weave thickness for polymer composites since one is limited to a single shot—a one-time impregnation.

B. RESINS, 3M AEROSPACE, JERRY SUNDSRUD

Jerry Sundsrud described one of 3M's latest resin products, PR-500, an aerospace-qualified, fluorene epoxy useful for RTM. Past issues associated with RTM resins included the uncertain quality of real-time resin mixing, a lack of high-performance resins, a lack of working knowledge of RTM, and a limited database (p. D-15). The new 3M product offers a stable, pre-mixed, one-part, quality control-tested resin. The chemistry of this resin allows its use in primary composite structures. 3M provides the needed experience and hands-on technical service to the user community. Mr. Sundsrud stated that 2,300 mechanical and environmental[9] test data points had been measured on the PR-500 to the date of this workshop and that 1,700 additional data points were expected by September 1995. Specific characteristics of the new resin (p. D-16) include excellent room temperature stability,[10] low viscosity at the recommended mold temperature, low shrinkage and exotherm during cure, and low moisture absorption after cure. The resin, which cures completely in 2 hours at 360 °F,[11] is inherently tough[12] with a relatively high modulus and mechanical properties. It also has performance capability (under hot/wet conditions) over 300 °F. Production capacity is in the hundreds of thousands of pounds per year. The resin is available in 1-,5- and 55-gallon containers.

One-part resin systems have several advantages (p. D-17), among which are no mixing mess, reduced worker exposure to chemicals, and no mix ratio concerns.[13] Other benefits (p. D-18) include the ability to pump directly from the shipping containers (which reduces the mess and chance of contamination), no degassing requirement, reduced heat exposure of the resin, no pot life concerns, and no solvent required for pump and hose clean-up. Other advantages also arise from the fact that it is a fluorene epoxy system (p. D-20). Mr. Sundsrud remarked that the low toxicity was not initially designed into the

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9 According to the speaker, the resin has been fully characterized in aircraft fluids and solvents.

10 Mr. Sundsrud indicated that the resin has a shelf life of several years at 0 °F. Under normal conditions, it may last from several weeks to months.

11 The injection time at 320 °F is almost 1 hour. This is proving to be adequate for > 99 percent of the applications to date.

12 The Compression After Impact (CAI) performance is greater than 40 ksi with graphite fiber reinforcement. At this point, the speaker mentioned that use of the SP 500-2 prepreg allows co-curing with the RTM process. A PT 500 tackifier, compatible with the resin, is used to hold fibers in place during the process. The importance of tackifier/resin compatibility in aerospace-grade RTM is highlighted in a paper present on pages D-30–D-43.

13 This statement is particularly true since 3M assures the mix ratio and completes all quality control testing.

resin but was a nice side benefit. The latent cure system, which was designed in from the beginning, results in an environmentally friendly process with minimal clean-up. The material has better flame retardance than other standard epoxies. The fact that other product forms are available with the same chemistry means that prepreg, for example, can be used for local reinforcement. A Society of Manufacturing Engineers paper present on pages D-44–D-54 describes in more detail the benefits of using a one-part resin system for aerospace RTM parts.

Mr. Sundsrud noted that nine applications were currently in production and flying[14] and that more than 200 parts are in development, included among which are rib section components for the Advanced Fighter aircraft (p. D-21). One of the components (p. D-24) was a vent louver in the MD-80 and MD-90 aircraft (p. D-25). McDonnell Douglas was able to replace a 60-piece aluminum assembly with a one-piece RTM component. Benefits included a reduced number of fasteners, which led to reduced weight (3.6 to < 1.6 kg) and a > 50-percent reduction in maintenance costs. 3M PR-500 is currently qualified to 11 customer specifications with more in process. Their existing Process Control Documents (PCDs) were approved by an Original Equipment Manufacturer (OEM). The manufacturing plant is qualified to ISO (International Standard Organization) 9002. The speaker also mentioned that the Navy (Warminster) is funding a processing study that includes process modeling and use of sensors to aid in process control.

The cost issue is important in the application of composites, regardless of how they are processed. The bar graph on page D-26 illustrates the contribution of resin cost to that of the RTM finished part cost. This graph shows effects at three different resin costs ranging from $22.50 to $45.00 per pound. There appears to be little effect on the finished part cost with different resin costs. The table on page D-27 shows the data that were used to create the graph on page D-26. Mr. Sundsrud concluded that, because of the lighter weight and design advantages of composites, a composite part costing over $300 per pound can cost effectively replace an aluminum part at $200 per pound.[15] In response to a question about the quantity of material that must be sold to reach a part cost of $25.00 per pound, Mr. Sundsrud replied that he did not know but he thought that such a goal was

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[14] Components are flying on the Boeing 777 (p. D-22), McDonnell Douglas MD-90, the ATR 72 (propellers), the Westland Sea King helicopter, and the Sikorsky S61 and HH3 helicopters (p. D-23). The helicopter component is a heated inlet duct for deicing. Heaters are molded into the composite.

[15] He observed that since composites are lighter weight than aluminum and complex parts are more labor intensive, composite finished part costs can range from $200 per pound to more than $2,000 per pound.

achievable depending on the volume and fiber type. A relative cost disadvantage is associated with two-part resin systems: mixers must be cleaned (e.g., pp. D-51, D-52).[16] The "melt-on-demand" system used for the one-part system (p. D-53) is much simpler and, therefore, less expensive. LtCol Obal inquired if this was a quality or cost savings issue. Allan Samuels noted that it was, in essence, a reliability issue. The cost is associated with scrap material.

Page D-28 summarizes the items requested in the invitation letter to the workshop. Most of these items have already been discussed in the previous paragraphs. Mr. Sundsrud stated that the fluorene epoxy had a glass transition temperature (T_g) of 400 °F.[17] He thought the performance of a composite made using this resin would be 350 °F, maybe 400 °F for a few minutes. When asked about the largest part fabricated, Mr. Sundsrud described a keel beam (10 feet long, 3 feet high, 2.5 feet wide) made for the Comanche helicopter. The part was manufactured using flexible internal tooling. One interesting comment was that the PR-500 has been extensively evaluated and the safety and health results were extremely favorable. The Environmental Protection Agency (EPA) requirements to prove product safety are extremely costly and generally discourage the development of new resin chemistries. Quality control procedures were briefly discussed in response to a question from Janet Sater. 3M prefers viscosity and differential scanning calorimetry (DSC) and high performance liquid chromatography (HPLC) because they provide adequate data to ensure product quality and because the procedures are relatively simple. Resins are evaluated on a batch-by-batch basis. LtCol Obal asked if 3M provided a warranty. According to Mr. Sundsrud, 3M does provide warranties, noting that additional tests are conducted as needed to address particular environments for individual customers. He emphasized the importance of accurate specifications. The speaker stated that incoming/receiving inspections are performed by the customer. Typically, they repeat certain, selected tests conducted by the supplier. The customers are testing for product reliability not liability. Liability is something for which all people in the product chain are responsible. In response to another question, Mr. Sundsrud replied that users must build confidence in the suppliers. He did not believe that the supplier could take any particular action to increase user confidence in terms of quality control. He mentioned that quality control was a trivial part of the finished component cost. Process certification is important

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16 The impingement mixers are very expensive and must be taken apart to be cleaned.

17 He indicated this resin T_g was tailorable and could be pushed to 450 to 460 °F.

to both the supplier and the user. Although PCDs are difficult to live with, Mr. Sundsrud believed they are effective.

Concluding remarks focused on when to use RTM for aerospace components (p. D-29). Preconditions to be satisfied include the following: composites are desirable, the RTM resin meets the design criteria, and the tooling is affordable. Reasons for selecting the RTM process over other composite processes include requirements for manufacturing cost reduction, tight tolerances for the inner and outer mold lines, or part count reduction. Another factor would be RTM component cost relative to the metal baseline concept. Lower is more attractive. Perhaps most important, at least to the composite supplier community, is the fact that the work experience obtained may lead to confidence in the process and increased future use.

C. RESINS, CIBA-GEIGY, ANDY WANG

Mr. Wang described RTM resin products of the Polymers Division of Ciba Geigy, noting that the Ciba Composites Division produces prepreg. Ciba produces a broad range of specialty polymers although he remarked that some customers purchase the components and mix their own resins.

General requirements for RTM resins include low viscosity, long pot life, and good thermal/mechanical properties (p. D-56). For advanced RTM systems, however, one-component resin systems are quite desirable as are toughened resins with properties equal or better than those of prepreg resin systems. The list of Ciba RTM products, given on p. D-57, includes resins—several types of epoxies, BMIs, cyanate esters, and polyimides—and various types of hardeners.

Mr. Wang described four different products in more detail (p. D-58). GY 282/HY 310 and MY 721/HY 5200 are two-component systems of interest. The GY 282/HY 310 system is considered a general purpose resin. It is a low viscosity resin system and can be processed at room temperature. Page D-59 shows the typical properties of each component. The graphs on page D-60 show the pot life at temperature (25 °C, 40 °C) and processing window at temperature (60 °C, 120 °C). Mr. Wang mentioned that after about 1 hour at 25 °C the viscosity increases from about 3,000 centipoise (cps) to 6,000 cps. Mr. Wang mentioned that 80 °C is a typical mold temperature. The required vacuum pressure is just enough to draw resin into the mold. A processing advantage associated with this resin is that no heated lines are necessary, as illustrated on p. D-61. Page D-62 gives typical composite properties at room temperature and 82 °C (180 °F). Test specimens

were made in a 14 in. × 14 in. × 0.114 in. mold using AS4 fabric (0.54 volume fraction). The laminate was cured for 30 minutes at 80 °C, followed by 2 hours at 150 °C. Page D-63 shows the typical properties of the MY 721 and HY 5200 components. The MY 721 component has high viscosity. It is a semi-solid at room temperature, so it must be heated before mixing. As indicated on page D-64, the viscosity behavior as a function of time at temperature is quite different from the other two-component system. The time necessary to reach high viscosities is considerably longer. The required pressure to fill the mold is about 10 psi. Using this resin for RTM requires a pressure pot and, possibly, heated resin lines (p. D-65). Page D-66 shows typical composite properties for temperatures ranging from room temperature up to 177 °C (350 °F). The test laminates were cured for 2 hours at 177 °C.

The XU MV 723 resin is a one-component system with the hardener suspended in the resins. It is a stable paste at room temperature (p. D-67). Its out-time at room temperature is 1 month, but the suggested storage temperature is 40 °F for a 1-year shelf life. The graphs on page D-68 show viscosity as a function of time at temperature in terms of pot life and processing window. Mr. Wang noted that the hardener starts dissolving at 80 °C. This process apparently occurs within just a few minutes. The gel time is 20 minutes at a 177 °C cure temperature, and the cure time at this temperature is 4 hours. Page D-69 illustrates the processing system required for RTM. The heated platen pump melts that surface layer. The resin slurry travels through the tube to a trough or moat around the mold shape. This is the point where the hardener dissolves. If the hardener is not dissolved here, the fiber preform will act as a filter and, as a result, the resin will not cure properly. An advantage of this hot-melt system is that there are no volatiles. Typical composite properties are shown for temperatures ranging from – 54 °C (– 65 °F) to 149 °C (300 °F).

The 93-104 resin is a one-component, toughened system (p. D-71). This developmental resin contains some multi-functional epoxy and is stable for 1 year at 40 °F. In response to a later question, Mr. Wang indicated that the resin could actually survive 18 months with no apparent changes in viscosity or gel time. It can be processed at room temperature. An interesting characteristic of this resin is its extremely high viscosity at 30 °C—11,000 cps—which decreases to 40 cps at 100 °C (p. D-72). This resin has a 22-minute gel time and 4-hour cure time at 177 °C and a pot life of 160 minutes (to 1,000 cps) at 100 °C. Pages D-73 and D-74 show neat resin properties and typical composite properties, respectively. According to Mr. Wang, the 93-104 resin is easy to

process and uses a unique toughening approach. The composites exhibit good fracture toughness and CAI properties. Mechanical properties up to 180 °F seem quite reasonable and balanced. Also, the technology used in its manufacture is comparably inexpensive.

Several questions were raised about quality control, which Mr. Wang illustrated by example. Ciba is providing polyimide resins for investigation in the High-Speed Civil Transport (HSCT) program. For Boeing, the prime contractor, product liability is most critical. There is a requirement for a 65,000-hour thermal aging test along with other very strict requirements. Ciba must work with Boeing to certify the raw material and the process. Once certification is complete, nothing can be changed. Another attendee inquired about mixing times for two-component systems. Mr. Wang replied that 10 minutes was usually adequate because of the low viscosities, but he noted that a mixing tank was necessary and the resin must be degassed. Dr. Parnas mentioned that one-part systems were used to accelerate the speed of the chemistry. Gary Wonacott asked about higher temperature resins. Mr. Wang indicated that, essentially, the same BMI resin used to make prepreg could be used for RTM although toughened BMIs, which Ciba also uses to make prepregs, are difficult to use for that purpose. Gray Fowler pointed out that the cyanate esters offer the highest temperature capability for RTM resins today. In response to a question about resin flow limits, Mr. Wang indicated that a resin viscosity of 500 cps was required to wet out fabric. A resin flowing at 1,000 cps would work but it would be more difficult.

D. RECENT PREPREG SUPPLIER HISTORY, IDA, JANET M. SATER

Because of the difficulty in arranging for prepreg suppliers to participate in the closed mold workshop, Dr. Sater thought it was relevant to include a brief discussion of changes in the industry over the past 5 years or so. Her presentation focused specifically on the prepreg industry although she noted that the flux in this part of the composite industry was indicative of the overall flux in the industry. Two sources were used for information on prepreg suppliers of the late 1980's: *Engineered Materials Handbook, Vol. 1, Composites,* ASM International, Ohio, 1987, and *Composites: An Insider's Technical Guide to Corporate America's Activities*, The Turner Moss Company, New York, 1989. The list on pages D-78–D-82 is limited to companies believed to be producing aerospace-grade prepreg materials and includes 23 companies, many of them small, with facilities in the United States. These companies are not necessarily U.S. owned. Typical materials produced by these companies include various fibers in epoxies, BMIs,

polyimides, phenolics, and thermoplastics. Production levels range from research quantities or custom orders to more or less standard products.

Pages D-83–D-84 provide incidents of prepreg industry down-sizing. For example, BASF Structural Materials sold Narmco Materials, Inc., a maker of prepregs and advanced composites, to American Cyanamid's Cytec Division, which then became the second largest prepreg operation. In October 1993, American Cyanamid spun off Cytec Industries and Cytec Engineered Materials from their Engineered Materials Division. Amoco Performance Products sold their advanced composites technology and prepreg operations to Hexcel Corporation, Quadrax Corporation, and ICI Fiberite in October 1993. In December of that year, Hexcel went into Chapter 11. They emerged from bankruptcy in February 1995. S.P. Systems was put up for sale sometime during 1993. A report in a recent issue of *Performance Materials* (Vol. 10, No. 21, July 17, 1995) indicated that S.P. Systems was being bought by Pendorf Group. This same issue of *Performance Materials* also revealed that Ciba-Geigy plans to purchase 49.9 percent of Hexcel, which will buy Ciba Composites for $80 million.[18] A definitive agreement was reached during the third quarter 1995, with completion of the transaction expected by the fourth quarter. Another interesting move was identified in another recent issue of *Performance Materials* (Vol. 10, No. 23, August 14, 1995): ICI plans to sell its Tempe, AZ-based Fiberite composites unit to a partnership of DLJ Merchant Banking (New York City) and Carlisle Enterprises (La Jolla).[19] The deal was confirmed in *Performance Materials* (Vol. 11, No. 3, November 6, 1995).[20]

The current list of suppliers of aerospace-grade prepreg materials was culled from four primary sources:

- *Composites: An Insider's Technical Guide to Corporate America's Activities*, The Turner Moss Company, New York, 1994
- *PM Strategies Critical Business Intelligence on the Key Corporate Players in Performance Materials*, Garrett Communications, Inc., 1993

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18 An article in a more recent issue of *Performance Materials* (Vol. 11, No. 2, October 9, 1995) indicates that Hexcel will provide $25 million in cash and an estimated $45 to $50 million of subordinated debt (the exact amount will be determined after closing).

19 This partnership "has extensive aviation, aerospace and commercial experience," according to Carl Smith, the new president and chief operating officer under Carlisle. Smith believes this combination will help Fiberite grow and increase its industry position. (Additional, complementary acquisitions are likely.)

20 The deal also involved a quick ICI settlement with XXsys Technologies in San Diego. XXsys claimed they had a mid-1994 agreement with Fiberite giving them first right to buy.

- Various issues of *Performance Materials*, August Pacific Press, 1995
- Various issues of *High Performance Composites*, Ray Publishing, Inc., 1994–95.

Again, there are 23 companies, many of them small, with facilities in the United States. However, a number of companies have left the business, and others have stepped in to take their place.

Dr. Sater concluded with a summary of issues facing the composites industry in general and the prepreg industry in particular. The flux in the industry is obvious with mergers, sell-outs, dropped product lines, and plant closings being the normal course of action. Aerospace markets are also quite obviously shrinking. Process costs associated with tooling, fabrication, and assembly continue to be relatively high. The fact that the domestic sources of carbon fiber are limited to two companies—Amoco for poly-acrylonitrile (PAN) and pitch fibers and Hercules for PAN fiber—is considered a problem by some.[21] Production of aerospace-grade prepreg materials in large quantities is limited primarily to a few companies in the United States: ICI Fiberite (United Kingdom, soon to be United States), Cytec (United States), Hexcel (United States), and Toray (Japan). Foreign competition has become an increasing concern. Note that two of these U.S.-located companies are foreign owned. In fact, Toray is a significant supplier of material for the Boeing 777, one of the very few real applications for aerospace composites. However, much of the flux in the prepreg industry can be linked to an overcapacity in production capability combined with shrinking markets. Several material suppliers have observed that the multiple and variable quality standards and certification requirements set by the users also can be a substantial problem.

E. PREPREG TECHNOLOGY, ICI FIBERITE, JANET M. SATER FOR PAUL SCHMITZ[22]

ICI Fiberite is one of the largest suppliers of prepregs for advanced thermoset composites. Available resins for these materials include toughened epoxies, cyanate esters, bismaleimides, and polyimides, among others (p. D-93). Pages D-94–D-98 identify

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21 Perhaps more by the users and part fabricators than the prepreg suppliers.

22 ICI was unable to participate in the meeting due to their recent buy of BP prepreg technology. However, the company graciously agreed to put together a package on their products for presentation by Dr. Sater. The presentation was expanded to include some information presented at the Graphite-Polycyanate Workshop from June 1993 as well as some information in the literature on QC methods.

specific resin series in each category. The toughened epoxy 977 series (p. D-95) resins, cured at 350 °F, have a blended mixture of thermoset and thermoplastic. The individual resins have varying degrees of toughness and compressive properties. The BMI 986 resin (p. D-97) has a 370 °F cure temperature and can be used to 425 °F in dry conditions and to 325 °F in wet conditions. The polyimide resins, 944 and 966C, have cure temperatures that range from 350 to 600 °F, and these resins are useful in high-temperature applications. A range of fibers are available for use in prepreg materials (p. D-99): carbon, both E and S-2 fiberglass, aramid (Kevlar®), and quartz. The advanced structural materials community is very interested in carbon fiber because it is available in a wide array of strength, modulus, and strain combinations (p. D-100). It is produced from either PAN or pitch precursors. As mentioned previously, Amoco is the sole domestic source for pitch-based fiber. PAN-based fibers are produced by both Amoco and Hercules.

As of June 1993, ICI Fiberite was using two manufacturing approaches for making prepreg (or towpreg): solution treating and hot film melting.[23] At that time, current capabilities of the solution treatment facility (p. D-101) included a maximum fabric or mat width of ≤ 34 inches, a maximum of 4 tows for FX products, and a furnace temperature of ≤ 600 °F, and the drum winder was limited to ≤ 12 inches in width and 72 inches in length. The hot film melt process was being used to make uni-directional tape products (p. D-102). For this product, fiber areal weights[24] could range from 30 to 380 gm/m^2, resin areal weights could range from 21 to 400 gm/m^2, and tape width could range from 1 to 24 inches. At that time, ICI Fiberite was able to use several different backing papers. They were also capable of filming highly filled resin systems and pseudo hot melts.

Current product forms, presumably made using these same methods, include roving, woven fabrics, and uni-directional tape. Roving consists of single or multiple tows of fibers coated with resin (solution treatment approach) and wound on spools (p. D-103). This product form is most useful for filament winding. Several types of woven fabric prepregs are available (p. D-104): uni-directional (up to 95 percent of fibers at 0°), bi-directional (0/90° standard weave, ± 45°), hybrid (mixture of fibers), non-crimp (heavier fibers interwoven with light carrier fibers), and stitched, multi-layered fabrics (bi-directional fabrics stitched with ± 45° fabrics). Fabric prepregs are most often made

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23 Information on prepreg manufacturing methods was taken from the following source: J.M. Sater and M.A. Rigdon, "Graphite-Reinforced Polycyanate Composites for Space and Missile Applications," IDA Document D-1454, Institute for Defense Analyses, November 1993.

24 Achieving low fiber areal weights requires higher resin contents and small tow sizes.

through the hot film melt approach. Tows in the uni-directional tape (p. D-105) are impregnated with resin as the tape is made (solution treatment approach).

In response to the workshop sponsor's initial letter request, Dr. Sater discussed quality control methods that would be appropriate for all parts of the prepregging process, from raw constituent materials to final prepreg product.[25] The list is fairly inclusive but note, however, that all makers of prepreg product forms may not use all the identified quality control methods. In addition, such a complete testing program may not be run on every batch of materials. It depends to some extent on the customer requirements and ultimate end use. Material forms that can be tested include the uncured resin (p. D-106), reinforcement (p. D-106), cured resin (p. D-107), uncured impregnated system (p. D-108), and the cured impregnated system (p. D-109). For example, the uncured resin would be evaluated for composition using HPLC, infrared spectroscopy (IRS), gel permeation chromatography (GLC), and/or DSC. The uncured resin would also be evaluated for processability [i.e., measurement of gel time and volatile content and rheometric dynamic scanning (RDS) viscosity]. Resin film thickness and areal weight would be other quality control concerns. HPLC, IRS, and DSC also would be used to evaluate the composition of uncured impregnated systems. Processability for these uncured systems would be evaluated by measurement of resin content, fiber volume fraction, RDS viscosity, gel time, volatile content, tack, and drape. Uncured prepreg density, thickness per ply, and process yield may be other important quality measures.

ICI Fiberite included data sheets for their materials in the information package sent to Dr. Sater. The data sheets include information on neat resin curing conditions and properties, typical mechanical properties of uni-directional, carbon fiber-reinforced, composite laminates, and product safety. There are data sheets for the following prepreg materials: 977-1 (pp. D-110–D-114), 977-2 (pp. D-115–D-120), and 977-3 (pp. D-121–D-126) toughened epoxy systems; 954-2A (pp. D-127–D-132) and 953-3 (pp. D-133–D-137) cyanate resin systems; the 986 bismaleimide system (pp. D-138–D-143), and the 966D polyimide system (PMR-15) (pp. D-144–D-146).

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[25] Information on quality control methods was obtained from *Composites Volume 1 Engineered Materials Handbook*, ASM International, Materials Park, Ohio, 1987: W.T. McCarvill, "Prepreg Resins," pp. 139–142; F.S. Dominguez, "Unidirectional Tape Prepregs," pp. 143–145; G.E. Hansen, "Tests for Reinforcement Fibers," pp. 285–288; L.C. Hopper and G.E. Sauer, "Properties Tests for Matrix Resins," pp. 289–294; R.H. Erickson and R.E. Allred, "Fiber Properties Analysis," pp. 731–735; and G.L. Sauer, "Resin Properties Analysis," pp. 736–737.

IV. COMPOSITE PART FABRICATORS

A. RESIN TRANSFER MOLDING, MDA, JERRY LEHMAN

Jerry Lehman elaborated on the RTM manufacturing aspects related to three programs: the LCCW program, an RTM program through the GLCC, and RTM components on the F/A-18E/F (p. E-2). As mentioned previously, several manufacturing processes including RTM, pultrusion, compression molding, IM, and others, were investigated under the LCCW program (p. E-3).

Manufacturing details were provided for five of six RTM components for the LCCW program: strongback, nose, fin, dispenser tube, and bulkhead. All the parts were built for MDA by Design Evolutions 4, Inc. although Mr. Lehman pointed out that Brunswick (now Intellitec) used internal funds to fabricate strongback parts. One advantage of this program not commonly possible for acquisition programs was that the components could be adapted to accommodate the process.

- The *strongback* (p. E-4) was fabricated from carbon/epoxy composite materials supplied by Hexcel and Shell Chemical. The aluminum tooling selected by the contractor was integrally heated and included three injection ports and multiple bleed vents for air removal (p. E-5). Page E-6 shows fabrication process steps. Although the part has a fairly simple shape, preform tolerance control and part removal were issues of concern. "Lessons learned" included using duplicate part tooling to fabricate the preform, incorporating a tool ejector system to ease part removal, and minimizing the number of air vents to decrease tool preparation time (p. E-7). In response to a question from Gary Wonacott, Mr. Lehman indicated that the strongback was post-cured outside the tool.
- The *nose* component was fabricated from E-glass/Syncore/epoxy, and E-glass/Syncore/BMI materials were provided by Hexcel, Shell Chemical, and Dexter Hysol (p. E-8). The contractor also selected integrally heated aluminum tooling for this design. This tool consisted of three segments with a segmented core, two injection ports, and four bleed vents (p. E-9). Pages E-10–E-11 show the fabrication process steps. The fabricator experienced problems with the Syncore during the RTM process. Fiber motion was observed in this part more than it was observed in others because of its shape. The injection

sequence and ply configuration also were found to affect this fiber motion (p. E-12).

- The *fin* was fabricated using stitched carbon/epoxy and carbon/BMI composites, foam core materials, and aluminum fittings provided by Hexcel, Shell Chemical, and Rohm Tech (p. E-13). As for the other components integrally heated tooling was selected. There was only one vent for air removal[1] (p. E-14). Pages E-15–E-17 show the fabrication process sequence. Use of stitched preforms resulted in reduced ply lay-up time. The fabricator also observed that the BMI resin system was not as sensitive to processing temperature as initially believed (p. E-18). Mr. Lehman also noted that the Rohacell foam was not able to withstand an unsupported post-cure process step at 490 °F. Gary Wonacott asked if MDA compared the RTM process with compression molding for this component. Mr. Lehman indicated the pressures arising during compression molding were too high and would crush the core. Using compression molding would, therefore, result in several extra process steps. In response to a question from Dr. Ho, Mr. Lehman commented that a vacuum and 100 psi pressure were required for resin flow.
- The *dispenser tube* is a somewhat more complex part (p. E-19). It was combined with a cover shell for a joining demonstration (p. E-20). Design Evolutions 4 fabricated this component from stitched E-glass- and carbon-fiber-reinforced epoxies supplied by Hexcel and Shell. The fabricator selected integrally heated composite tooling with a collapsible mandrel for this application (p. E-21). The photographis on pages E-22 and E-23 show the fabrication process steps. Mr. Lehman noted that composite tooling does offer some potential for cost reduction but there are durability concerns. Other "lessons learned" include using stiffer mandrels to prevent part deflection during cure and minimizing dissimilar tooling materials to prevent coefficient of thermal expansion (CTE) mismatches (and reduce residual stresses). The speaker also mentioned the time required to drill out the excess cured resin in the vents and suggested that the vents be pulled out before resin gelation to circumvent this step.
- The *bulkhead* component is the most complicated, as illustrated on page E-25. E-glass- and carbon-fiber-reinforced epoxy preforms provided by Hexcel and Shell were used in the fabrication. Integrally heated aluminum tooling contained a moat-type gate and multiple vents (p. E-26). Mr. Lehman remarked that the number of vents used—33—was probably overkill. Since there was little process modeling and/or simulation done as part of this program, it was thought better to err on the side of safety. He did mention,

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1 According to Jerry Lehman, finding the right location for the vent took several trials.

however, that this component would be a good candidate for a mold-filling simulation.[2] Page E-27 shows the fabrication sequence. Difficulties with preform design and tolerance control were noted, particularly for the spokes. The fabricator concluded that removing parts from the mold would be easier with a tool ejector system and that reducing the number of vents would decrease tool preparation time (p. E-28).

During the course of these summaries, several questions were raised. One attendee inquired about use of sensors on parts during the process. Mr. Lehman replied that thermocouples were used to measure temperature during cure, but there were no other sensors. He further commented that there was very little process modeling done as part of the LCCW program. LtCol Obal asked, "If 20 or 30 parts were made, would they all be the same?" Mr. Lehman replied that he "wouldn't say yes." Dr. Parnas observed that several programs throughout the world are addressing processing science issues. He emphasized the need to get away from technician-dependent quality and to establish design guidelines. LtCol Obal raised a question about how MDA keeps its experience base from a program like the LCCWQ, which is not a system production program. Mr. Lehman replied that the technology is used in training through design guidelines for engineers, sketches, and engineering drawings. He noted that MDA does not want to reinvent the wheel every time a new part is designed.

To conclude his presentation, Mr. Lehman suggested R&D directions in several topical areas including preforms, resin systems, tooling, and process equipment (p. E-29). Cost and tolerance control continue to be significant issues with the preforms and should be addressed. When asked about the bulk factor, the speaker replied that the bulk factor is minimized for MDA by considering parts with essentially two dimensions. Jerry Lehman thought tradeoff studies examining preform complexity vs. ply lay-up time would be useful. In terms of resin systems, he mentioned the need for optimized RTM resins, the lack of a good high-temperature resin for RTM, and the need for new binders. He further observed that even though the manufacturer wants to minimize the number of materials used in a system, the current resin was designed for prepreg lay-up, not RTM. This is a problem for Brunswick (now Intellitec). Other improvements are desired for release agent durability. Tooling is very important in fabricating quality parts. Unfortunately, tool design is most often accomplished by a "trial and error" approach. This approach must be

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2 Richard Parnas noted that there are about 10 codes available for mold filling. Unfortunately, industry buy-in, at least so far, appears to be minimal.

reassessed if the technology is to see widespread use. Mr. Lehman believed that standardized gating and venting concepts were needed for tooling as were resin flow models. Use of in-process control methods is thought to be another important way to improve part quality. In this regard, different sensors should be evaluated and incorporated into the process. Another attendee asked about witness samples. Mr. Lehman indicated that witness samples were not made because it was known that the part would be cut up for evaluation. Gray Fowler pointed out that witness samples can be misleading depending on where the sample is with respect to vents and injection sites. Charley Bersch (IDA) asked if composites would be used in the bulkhead and strongback. Mr. Lehman indicated that metals would probably be used in this case because the structures experience highly concentrated loads. Mr. Bersch also pointed out that stitching was not the answer to 3-D reinforcement. Mr. Lehman agreed with the statement and commented that 3-D preforms may be useful in wing structures from a damage perspective but are very expensive. He further stated that composites are good for in-plane loading conditions no matter what process is used. In response to a question about porosity, Mr. Lehman said it is a couple percent on average but that it occurs in mostly localized regions.

B. RESIN TRANSFER MOLDING, TEXAS INSTRUMENTS (TI), GRAY FOWLER

Gray Fowler kicked off the Tuesday morning session by describing TI's RTM activities, particularly those activities focusing on tooling, materials, and production (p. E-31). In the early days of the HARM missile program, TI was using Hexcel F155 prepreg for the antenna. When the company was threatened with a second source, they undertook a study to upgrade the performance and lower the cost of the antenna. At that time, they were making 230 missiles per month. The fabrication time per antenna unit was 3.13 hours using compression molding and vacuum bag processing, as shown on p. E-32. This production rate required six people (two per shift), running large presses and tools. Machine and tool downtime led to significant production cost increases. By switching to RTM, the fabrication time per unit was decreased to 1.44 hours (p. E-32). According to Mr. Fowler, the current rate is 1.33 hours. Currently, TI is making only 220 parts per month, a production rate that requires only two people over one shift. The machinery is operated continuously for 5 days, and then shut down once all the parts are made.

The next segment of this presentation focused on tooling. Since TI uses slightly higher pressure in their RTM process,[3] steel offers the best performance for prototype tools (p. E-33). It has excellent durability and is very stiff, but the machining costs are high. Mr. Fowler noted that the size of the part affects the size of the chunk of steel required to make the tool. The parts made for the HARM are hand held so the tool is relatively small, weighing about 25 pounds. Aluminum is another prototype tooling material with moderate stiffness. It has low durability, although its machining cost is more moderate. Tool deflection has been observed in unclamped areas. It can be made more durable (abrasion resistant) by anodizing the surface. Tool durability is important because technicians remove flash with razor blades. The two other aluminum tool materials (p. E-34) are based on Stereo-Lithography Approach (SLA) rapid prototyping techniques. The hard-anodized, SLA-cast aluminum offers good durability and moderate stiffness at a lower machining cost. The SLA-aluminum-composite offers the lowest machining cost but also low durability and a lower stiffness. At this point, LtCol Obal inquired about the amount of tool cost in the design phase. Mr. Fowler replied that since rapid prototyping capabilities allow quick turnaround for design and production tools, tool cost was less of an issue; however, he noted that machining was still the most significant portion of the tool cost (6–8 times, as an educated guess). He also mentioned that ProEngineer, ProMold, and ProSheet metal software packages were available to help with tool design. He further observed that the company with the most advanced machining capability has the best advantage in terms of being able to reduce tool cost. In response to another question, Mr. Fowler indicated lead time for tools is typically 3 to 6 months depending on part complexity and whether an outside vendor is machining the tools. LtCol Obal then asked if a revolutionary advance in tools was required. The response was an emphatic yes. Tooling that is adaptable or that can be easily repaired is most desirable. The best tooling for high production rates, particularly for composites, is steel with ion nitride surface hardening[4] or through hardening treatments[5] (p. E-35).[6] For low production rates, hard anodized aluminum or non-hardened steel are appropriate. In terms of quality control, Mr. Fowler

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3 Mr. Fowler indicated TI uses a hydraulic pressure system with a pressure capability of 100 to 700 psi, noting that they usually end up backing off the pressure. The prepreg resins TI uses are semi-solid at room temperature, thus, the need for higher pressures. Using prepreg resins results in higher quality parts.

4 The P-20 steel is not weldable; however, this material does have a very good surface finish.

5 The 440 steel is weldable. These materials require extra care in machining and in use.

6 Tool wear occurs because the fibers are being compressed in the tool to increase the volume fraction.

stated that TI does not inspect parts but that all of the molds are individually certified[7] as are the preform fabrication tools. Operators also are certified through self-inspection and can make their own decisions rather than waiting for the quality control people to respond to a problem. TI uses in-house training because it saves cost in production. Near net tooling came from a TI "idea package" (basically IRAD) based on the concept of "zero machining": combining all features into a single package that does not require machining. These features might include holes, bosses, countersinks, and various types of stiffeners (p. E-36). TI tries to make a part within three attempts. The company has parlayed this concept into a couple of manufacturing products. Currently, they are investigating net molded aluminum inserts. Les Kramer asked if corrosion was a problem. Mr. Fowler replied that the aluminum is black-anodized which does not provide good corrosion protection in thin film form. Thermal expansion mismatch between the aluminum and composites is more of a problem. Steel offers a closer match. TI has experienced drilling problems in which the inserts were spun loose because of drill torque.[8] The SLA-cast aluminum composite tooling concept came from another TI idea package and is being considered for some applications. Mr. Fowler observed that although it is desirable not to use fasteners for joining, sometimes it is better not to consolidate everything. The speaker mentioned that Sandy Munro teaches a training course on how to make parts without fasteners. TI is considering using these concepts to produce real parts. LtCol Obal inquired about in-process monitoring. Mr. Fowler replied that if TI were making $250,000 prepreg parts they "would monitor like crazy." Since the RTM parts being fabricated are not that expensive, TI does not monitor the process in situ. Cure profiles are automated and monitored.

Properties of the raw materials, especially the resin, are important in ensuring the production of a high quality part by RTM (p. E-37). For the high-performance applications, TI uses a toughened cyanate ester resin from Ciba with a T_g of 290 °C, water absorption < 0.5 percent, and a cost of $20 to $25 per pound.[9] Mr. Fowler mentioned that TI has tried BMI resins, but water absorption, cost, and viscosity are significant issues. For mid-performance applications, a T_g up to 125 °C with water absorption of < 1 percent

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7 Every dimension is 100 percent inspected. The part being made has a conical shape so if the tools are not put together properly, fit problems will occur. According to Mr. Fowler, TI's quality control people took a long time to decide how to measure quality for this process.

8 Cutting oil was used in drilling.

9 The cyanate ester has a low viscosity, 100 cps, and costs $75 per pound. The toughener, B-30 (or L-10 or M-30), is a thermoplastic prepreg resin and costs $20 per pound.

is acceptable. Also, the cost is much less, ranging from \$3 to \$4 per pound. Mr. Fowler suggested that relief on B-basis allowables would be appropriate for fabricators, particularly for those in the missile business, observing that resin suppliers conform to the standards because they make money as soon as they are qualified since everyone else is essentially excluded. He further remarked that a "one-shot missile system is different from a man-rated aircraft." He also suggested that a Tri-Service material database be created, commenting that, at a minimum, agreement among the Services would be desirable. LtCol Obal emphasized the difficulty associated with the government leading such an effort, noting the example of the Long Duration Exposure Facility (LDEF),[10] and suggested that industry should lead. He also emphasized the need to bound the problem, again with industry assistance. Mr. Fowler mentioned that TI built several prototypes for the Navy using the cyanate esters. Unfortunately, the Navy did not want to switch from the epoxy since it was already qualified (an "if it ain't broke don't fix it" approach). TI then added 20 percent epoxy to the cyanate ester, which turned out to be acceptable to the Navy. Dr. Mohan Aswani raised a question regarding how company B would use data generated by company A. Mr. Fowler noted that everyone tests material, but everyone also uses different cure processes and fabrication procedures. Dr. Aswani then rephrased the question in this way: Assuming that company A makes a good part and company B makes a lousy part, where will the materials be tested and how will company C use the data? Mr. Fowler replied by citing an example. Although ICI Fiberite 9577 prepreg material was qualified by the Navy and B-basis allowables exist for it, the process must still be qualified. Quality features that must be evaluated as part of this qualification process include composition, mechanical properties, the manufacturing process, and the component itself. TI did not have to create B-basis allowables for the HARM application because it was not a primary structural component.[11]

Reducing production cycle time for a component has the added advantage of reducing cost because it reduces work-in-progress, the amount of tooling required, and the labor time per unit (p. E-38). TI is using fabrics for the HARM component and has invested \$50,000 in die cutting to cut the fabrics for the preform. The maximum size fabric

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10 The LDEF was a NASA Shuttle-launched space platform designed to test several advanced structural materials, coatings, and so forth in many different experiments. Originally designed to be in space for only a year or so, the Challenger explosion prevented its recovery until more than 5 years later. The amount of data to be generated—from the designed experiments and from the other subsystems required for operation—following recovery was expected to be substantial. Results are fractured at best. LtCol Obal indicated that no one trusts the data generated from LDEF and that data quality is uncertain.

11 Apparently, after 10 missile firings, it was decided to implement all the HARM upgrades at once.

that can be cut at TI is 18 inches wide × 2 feet long. Up to eight layers can be cut at one time. Mr. Fowler indicated that the operator takes 4 hours to cut the fabric for a complex part. Water cutting and laser cutting were mentioned as alternative processes. John Harrell remarked that laser cutting causes the end of the fibers to swell, behavior that is acceptable at ends but not for internal cut-outs. An ultrasonic knife cutter provides a really high quality cut, but it is an expensive machine, costing about $800,000. By using drapable fabrics, TI is sacrificing something in terms of properties but it allows for somewhat easier preform fabrication. Mr. Fowler observed that braid properties are an issue. These types of preforms are hard to characterize. "Snap curing"[12]—a short time at a cure temperature to set the dimensions of the part—offers reduced cycle and labor time (p. E-39). Once the dimensions are set (at the resin gel temperature), the partially cured component can be removed from the mold and be fully cured in a free-standing position in an oven. This "snap cure" process has been demonstrated for epoxies, vinyl esters, and cyanate esters. Thermocouples located in the tools are connected to a controller so the ability to control and monitor the process is limited by the response time and accuracy and precision of the device. Richard Parnas emphasized that the temperature in the tool, not in the part, is being controlled. For thin sections, the tool and part temperature can probably be assumed to be the same. Care is required for thick sections. Mr. Fowler stated that TI's process is semi-automated. The RTM process and the curing operations are automated, and cutting and lay-up are done by hand.[13] He thought that obtaining high-resolution information from embedded sensors and so forth had little value in missile production because of the high cost. If TI were making aircraft parts, they would probably do such monitoring. Since polyimide prepreg is difficult to process, in-situ monitoring is a sensible thing to do, particularly if only a few parts are being fabricated.

Production quality measures are based on a Six Sigma analysis (p. E-40). Six Sigma is a Motorola approach to quality in which 1 part in 1 million is unacceptable.[14] This concept is interpreted as three deviation process shifts. For example, if the substrate thickness is 20 mils, the acceptable deviation is ±3 mils.[15] Using this approach requires

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12 The specific sequence used by TI for the HARM component is as follows: a 7-minute ramp to 350 °F; hold for 6 minutes at 350 °F; follow with a cool-down with room-temperature air and liquid nitrogen.

13 Mr. Fowler remarked that tool costs are $15,000.

14 TI is currently at the 5.1 sigma level.

15 A part with a 23-mil substrate thickness is acceptable although a 24-mil part is not (even though it really works).

quantitative measures for what constitutes a good part and what constitutes a bad part. TI does collect and store process data through a controller interface. These data can be evaluated by lot, batch, and individual run if necessary. In response to a question from LtCol Obal, Mr. Fowler replied that robots are too complex. It is difficult to tell a robot how to fix something that is wrong. Dr. Parnas mentioned that robots are used for mold closing in the automotive industry. Indicators to show that the tool is closed are connected to a control system. If something is wrong, an alarm will alert a technician to a problem, which can then be fixed. He did observe the requirements for automotive/commercial industries and those for high precision industries are different. SPARTA developed a second generation mold closing system—a complex, 3-axis molding closing system—that was used in the fabrication of Javelin parts.

Mr. Fowler concluded his presentation with some comments on barriers that must be addressed to achieve the claimed cost reductions (p. E-41). Tooling appears to be key in achieving these cost reductions: alternatives to steel for prototype tooling to reduce nonrecurring engineering costs and delivery time; availability of durable, low-cost tools for low volume production; and increased use of near-net shape tooling[16] to reduce/eliminate machining, part count, and joining operations. He also thought that innovative joining techniques to eliminate mechanical fasteners should be developed. Other features (p. E-42) that could lead to reduced cost include relief of B-basis allowables, creation of a Tri-Serivce materials database, development of improved methods for making preforms. Mr. Fowler also emphasized the use of high-performance materials only where necessary. LtCol Obal inquired about the potential of hybrid tooling by combining prepregs and preforms (MMNM with RTM). Mr. Fowler replied that it was probably not cost-effective because it takes away the primary advantages of the RTM process (reduced cycle time and labor).

C. RESIN TRANSFER MOLDING, INTELLITEC, GERALD SUTTON

Jerry Sutton began by saying that Intellitec, a Division of Technical Products Group, Inc., used to be Brunswick. He emphasized the primary goal of RTM: to achieve equivalent performance to autoclaved or compression-molded parts at half the cost (p. E-45) What features make the RTM process attractive? Mr. Sutton mentioned dimensional control, off-line preforming, net-shape molding, and low emissions (p. E-46).

16 An example was given for a Proposed Paveway part design: by using near-net shape tooling, TI was able to reduce 326 parts (includes fasteners) to 8.

The RTM process is made cost-effective by reduced part count,[17] lower raw materials costs, reduced unit fabrication cycle times, the possibility to fabricate multiple parts per cycle,[18] self-contained operations and assembly control,[19] and potential for automation (p. E-46). The bottom line of what really gets it into production is low cost. As illustrated in the pie chart on p. E-47, labor costs are split 50/50 between fabrication and tool preparation/equipment set-up. Fabrication includes resin injection (20 percent) and preform fabrication (30 percent); the other steps include mold preparation (35 percent) and demolding (15 percent).

Intellitec can make parts having a maximum 4-foot diameter.[20] Simple tools rather than presses are used to close the mold, which is heated with oil. Resin mixing is done ahead of time. Sealing is one of the most critical parts of the process. One needs to be able to get air out of the mold and keep the resin in the mold. He commented that it is not very exciting when the seals work but that it is exciting when they do not work. He also commented that Intellitec does not make enough of any one component to warrant additional equipment investment, nor do they use enough of any particular resin to handle more than one injection system.

Critical RTM elements that must be controlled to mold a part successfully include tooling (most critical), preforms, resins, and processing (p. E-48). Tooling features include seals, temperature, resin flow, and dimensions. Important factors for the preforms include fiber volume fraction, orientation, and bulk factor. This situation can be complicated by the variety of preforms available, use of fiber sizing, and so forth. Having an acceptable resin viscosity and pot life are critical for complete infiltration of the preform in the desired time. Cost is also important and is usually related to the required component performance. To ensure that the first part produced is the same as the 4,000th part produced requires demonstrating process controllability, repeatability, and predictability. Use of the RTM process should not result in a knockdown factor because of some uncertainty about part quality and performance.

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17 Mr. Sutton indicated that a 25 percent reduction in supportability was possible because of the reduced part count.

18 Intellitec fabricates 2,500 parts per year and does 6 parts per mold.

19 This feature reduces or eliminates the need for secondary processes.

20 Apparently I-beams as large as this have been made.

Critical aspects of resin selection for RTM include its flow characteristics and processability, the component use temperature, and the price. Page E-49 shows the available resin systems and their corresponding price ranges. The 150 °F resins range from $1.50 to $3 per pound, but these materials are probably not acceptable for high-performance applications. The 350 °F epoxy systems range from $12 to $80 per pound, and some of these resins exceed the cost of the BMIs ($40 to $65 per pound).

Factors affecting RTM raw material quality arise from source variations, storage characteristics, and batch-to-batch variations (p. E-50). Source variations might include tow size, weaving, and sizing of the reinforcement, and the amount and application method of binder. Storage effects such as moisture, temperature, and age would be most important for the resin. Batch-to-batch variations may be observed in fiber areal weight, for example. Mr. Sutton indicated that the tests to be conducted are usually negotiated up front with the customer. These tests, which may be subcontracted to another facility, would duplicate tests done by the material supplier. Gray Fowler mentioned that TI performs extensive receiving tests but that Shell, Dow, and Ciba, the three major resin suppliers, all use different tests. This situation has cost and schedule impacts for the user and part fabricator. Mr. Sutton remarked on the differences between Air Force and Navy impact resistance requirements.[21] The Air Force loads the component to 500 ft-lbs and reruns the test to measure the failure strain. The Navy loads the component until damage is barely visible (1,500 ft-lbs) and then tests to measure failure strain.[22] The Air-Force-measured toughness was better than that of 3501-6 epoxy, a factor of three improvement over that obtained from the Navy tests.

Factors affecting the RTM process are temperature, pressure, component geometry, and preform (p. E-51). The two most important factors are the fiber volume fraction and the type of weave. Component geometry (features such as undercuts, radii, ply drop-offs, inserts, and complexity) is also critical.

Several photographs of components fabricated by Intellitec (not included here) were shown. One photo pictured a part with numerous vertical surfaces and thin walls. The part was designed to fix a corrosion problem. 2-D fabrics were used for the preform. Difficulties were associated with laying the fabric around sharp edges and corners and with

21 The Army is just beginning to address impact resistance requirements.

22 When the Navy tested the component after loading to barely visible damage, catastrophic failures were observed.

maintaining fiber alignment during resin injection. Part count was reduced from 37 metal pieces to 1 composite part. Stator vanes (72 per engine) and a spinner have been fabricated for turbine engines. Impact resistance is a critical property for this component. The RTM part was molded in a titanium ring using S-2 fiberglass. The unidirectional fibers were overwrapped by braiding, and a stainless steel screen was included for erosion resistance. Intellitec makes 2,500 of these components per year.[23] Nine hundred smoke grenade launcher tubes[24] have been fabricated for the Army, and 25,000 units are required. Intellitec started out by building a black aluminum part and then switched to a single-piece composite component using a fiberglass reinforcement. Intellitec also has provided a net-shape part design and tool for a coupling for a space application for Harris Manufacturing. The Navy has approved F-18 outer wing seals fabricated by RTM. Each aircraft has 98 outer wing seals. These seals are made using the already qualified 977-3 prepreg resin (since the Navy believes in one fiber/resin system on any aircraft).

Mr. Sutton provided a wish list for new materials (p. E-52). For resins, high performance/low cost resins and resins with low viscosity, long pot life, and no mixing (single-component system) are desired. Conformable fabrics and lower cost/value-added woven reinforcements are also desirable. Mr. Sutton remarked that J.P. Stevens makes conformable fabrics up to 60 inches wide but that minimum orders are 15,000 yards. Improvements in binder application also would be helpful. Lower cost, value-added woven preforms also are desired. To date, Intellitec's experience with 3-D preforms has not been good. The parts experienced high resin shrinkage and exhibited poor surface quality.

Intellitec has learned several lessons from their past experiences (p. E-53). One lesson deals with designing the part for fiber volume. Closed molding is fixed-thickness process requiring control of fiber volume and material density (areal weight) as well as control of the balance of the laminate (properties). For B-basis allowables, Mr. Sutton noted that industry is pushing to obtain RTM data. This push apparently was initiated by the GLCC and picked up by industry.[25] Most people think in terms of prepreg and autoclave. In addition, most people desire a high-volume fraction of fiber. A second lesson deals with optimizing RTM attributes. This optimization can be done by careful

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23 According to Mr. Sutton, the scrap rate is about 3 percent.

24 Only one tube segment was replaced with composites for the launcher system.

25 According to my notes, five or six companies have gotten together and selected resins to be evaluated.

selection of fiber architectures, resins, and tooling materials. Mr. Sutton stated emphatically that production tool design and requirements is not the place to save money. The success or failure of the process relies on tool quality. He also observed that most schedule delays have arisen from attempts to save money in tooling. He also emphasized that RTM is a flexible manufacturing approach that can help reduce cost. It is appropriate for certain classes of parts but not for everything.

Mr. Sutton next described a typical RTM implementation plan (p. E-54). In Phase 1, test panels will be fabricated and tested. For example, these panels would be tested to verify equivalence to prepreg composites (as was done for the F-18 component). Also included in Phase 1 are development of manufacturing and tooling plans, design support, cost analysis, and process specifications. In Phase 2, subcomponents would be fabricated and tested. Phase 3 is full-scale production. Mr. Sutton remarked that "one failure is broadcast more widely than 25 successes." He also indicated that he would rather build and test parts than develop B-basis allowables.

Mr. Sutton concluded his presentation with a brief summary (p. E-55), noting that RTM is gaining acceptance. Although new materials are solving some problems, he believes that more data are needed for continuing process acceptance. Charley Bersch pointed out a potential conflict: on one hand, predictable, reliable resins are desired to make predictable, reliable products but, at the same time, there is also a desire for higher performance resins. The question is which is more important. The response was that predictable, reliable products are most desirable because they increase confidence of the user. Tom Anderson commented that the materials/process moving target was disconcerting for Lockheed: they "don't like using new technologies because they can't make schedule." Some people disagreed with this comment since most believe RTM to be an established process. Les Kramer mentioned that the Department of Defense (DoD) is leaning toward commercial practices. Military specifications would only be used with a waiver. So far, most waivers appear to be more related to duplicative testing. DoD is beginning to rely more on data provided by the suppliers. He specifically mentioned some differences in how business is done in the Army and noted that acceptance of ISO 9000 standards helps commercial integration.

D. MATCHED METAL NET-SHAPE MOLDING, COMPOSITES HORIZONS, INC., MILTON ANDERSON

Composites Horizons makes polyimide (PMR-15) composite exhaust flaps (illustrated on p. E-57) for the Pratt & Whitney F100/PW-229 engine used in the F-16. Dr. Ho inquired about the maximum use temperature of the part, which is 600 °F although the operational temperature is 500 °F. The time at temperature for the component was not mentioned. Page E-58 gives details on the flap. This component replaced a titanium assembly.[26] There are 15 flaps per engine operating during afterburner use at temperatures up to 500 °F. They are made by an MMNM process using steel compression molding tools and CAREMOLD, a washout tool material, for internal ribs. The ribs are co-cured with the panel. The composite lay-up consists of 40 plies of 8 Harness Satin weave with 20 plies of uni-directional tape. Gray Fowler mentioned that TI makes a wideband radar component using thin-walled polyimide composites. Someone asked about how much the use temperature could be pushed. Mr. Anderson replied that the composite is cured at 600 °F but that damage on repeated excursions probably did not occur until well beyond the 500 °F operating level. The flaps are connected to the engine by titanium hinges and PMR-15 bushings, developed in the third generation. Apparently, there is an adhesive problem (high-temperature capability) between the PMR-15 composite and the titanium. Because of this problem, the design includes mechanical entrapment of the titanium hinge to ensure against bond failure. When the afterburner is on at high temperature, as shown on the test-stand-mounted engine on page E-59 and on the aircraft on page E-60, the flaps are articulated to their maximum extension. A factor of 4 improvement in service life has been achieved with the composite flaps.

Page E-61 lists the fabrication steps. Steel rule die cutting is used for cutting plies.[27] Mr. Anderson noted that polyimide is a fairly toxic material—it contains methylene dianiline (MDA)—so material handling is limited as much as possible. The CAREMOLD product is a Composites Horizons product. A castable, plaster-like mold material used for co-curing hollow cavities and so forth, CAREMOLD can be washed out with water. Lay-up is done by hand and is followed by an imidization step on each of two skins, an optimized compression mold cure cycle, and a free-standing post-cure step. The part is trimmed at the edges by waterjet cutting, and the castable mandrel is washed out. At this

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26 According to Mr. Anderson, the titanium assembly was welded and experienced cracking in the welded joints from in-service fatigue.

27 Mr. Anderson indicated that die cutting and water jet cutting are done by vendors.

point, it can be ultrasonically inspected (p. E-63). The component is quite complicated, as shown on page E-62. Over 1,000 have been made to date.

Problem areas (p. E-64) included the following:

- Co-cured/hollow close-out cavity. Secondary bonding created a problem because adhesives with capabilities to 600 °F are unreliable. In addition, the presence of a 3/8-inch diameter bushing hole in a 1-inch square hat section prevented the removal of solid tooling. The solution (p. E-65) was to use the CAREMOLD castable tooling to allow for co-curing and removal of tooling. This tool material can easily withstand the PMR-15 curing process and has the same thermal expansion as the composite. Apparently, the tool material is mixed in a blender (p. E-66). Page E-67 shows the actual mandrel. A question was raised about the attachment of the titanium end fittings. Mr. Anderson replied that the titanium end fittings are held in place by mechanical locking, not adhesives. There is no concern about secondary bonding. He also mentioned that the titanium bushing was replaced with the PMR-15 composite. In response to a question from Les Kramer, Mr. Anderson indicated that the titanium is treated to provide increased bonding.
- The 100 percent bulk factor of imidized PMR-15. The bulk factor of PMR-15 prevents net-shape molding of hat sections and would cause wrinkles on the outer skin during cure (p. E-68). The solution was a two-part imidization in which the inner hat-stiffened skin is imidized separately from the outer skin. The two halves are then combined during final cure.
- CTE differences to 600 °F. CTE mismatch[28] prevents net-shape molding and locks the part onto the tool during cooling (p. E-69). The problem arises because PMR-15 requires a 430 °F imidization cycle and a 600 °F, 1,000 psi cure cycle. The solution was to size the imidization tools to match the CTE of steel at 430 °F (pp. E-70–E-71), then to hot-load the press cure cycle at 450 °F. The part is removed from the mold at 400 °F.
- The long cure cycle time (8 hours). The standard cure cycle for PMR-15 is 8 to 10 hours (p. E-72). This cure cycle presents a problem in trying to attain a production rate of 5 parts per day using one press and tool. The solution was to optimize the cure cycle: 2.5 hours total per part (p. E-73) in the press (pp. E-74–E-75). The rest of the cure is completed in the free-standing condition.

[28] There is a factor of three or four difference between the steel and composite CTEs.

Composites Horizons is now on the fourth generation design, "probably one of the finest designs seen," according to Mr. Anderson. He emphasized the importance of the castable tooling. It makes it single-step curing possible, which is particularly important in curing polyimides for which secondary bonding should be minimized. In response to a question on part problems, Mr. Anderson replied that edges were a bit thin on some parts. The titanium end fittings were used to allow for easier removal if repair or replacement were necessary. LtCol Obal asked about the titanium/composite interface. The fitting was designed to withstand the locking strain. Mr. Anderson indicated that confidence came from the fact that the titanium is mechanically locked to the composite. He concluded with some benefits of the composite flaps: acquisition costs are much lower than for the baseline titanium assembly, and maintenance and supportability costs are also reduced because of the longer life of the composite components. An additional advantage was reduced weight although the specific weight savings were not quantified. Mr. Anderson said the Pratt & Whitney (P&W) specifications were incorporated into Composite Horizon's PMR-15 specification. He thought that more standardized specs were needed for PMR-15.

E. RESIN TRANSFER MOLDING, DOW-UNITED TECHNOLOGIES COMPOSITE PRODUCTS, ALLEN SAMUEL

Allen Samuel provided a different perspective, that of a subcontractor/supplier who has less freedom to choose the material or the process. Mr. Samuel mentioned that RTM was started about 30 years ago by Hamilton Standard for propeller blades. More advanced RTM methods were developed in the mid-1980's. The speaker then commented that the composites industry is "no longer in the time of goodness" as was the case during most of the 1980's. The opportunities of that time—large numbers of programs of varying complexity, high projected production rates, competition with investment casting, trades of weight for cost, maximum structural integration, special technologies enhancements[29]—have disappeared (p. E-76). Current and future opportunities are likely to include a limited number of new starts or improvements and low production rates. Funding for high-rate tooling enhancements will be even more limited. Mr. Samuel believed that a critical manufacturing mass should be developed, not a missile-specific manufacturing technology.

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29 Examples of technology enhancement programs included Tri-Service Stand-off Attack Missile (TSSAM), Tactical Munitions Dispenser Equipment (TMDE), Advanced Interdiction Weapon System (AIWS), Modular Stand-Off Weapon (MSOW), and Long-Range Conventional Stand-Off Weapon (LRCSOW).

This approach is dual-use. DoD's needs should rely on the baseline, already-qualified RTM process.

RTM is becoming more accepted for application in man-rated systems (p. E-77). The key airframe program to increase acceptance of RTM components is the Boeing/ Lockheed Martin/USAF F-22. Propulsion systems programs investigating RTM include the Advanced Research Projects Agency (ARPA) Advanced Composites Propulsion fan exit case, the P&W Joint Technology Demonstration Engine (JTDE) inlet case, and the PW4084 fan spacer. These programs offer the material and process validation for a range of very complex parts. They also provide a beginning production base for advanced RTM. Mr. Samuel indicated that the material database is growing, and RTM has been shown to be mechanically equivalent to prepreg materials. The baseline process is defined and is considered to be robust, and control is achieved by details and rigid process specifications. Quality levels matching requirements for primary structure have been met. RTM-based designs are competitive with complex metal designs and offer weight and cost savings. Issues that need to be addressed for missile applications include design, cost, and quality (p. E-78). Traditional metal designs should not be duplicated to be cost effective. Design approaches to consider heat transfer, electrical shielding, and fastener installation also will have to be addressed. In terms of cost, industry willingness to pay for performance must be assessed. In this regard, it will probably be important to show that composites are cost-competitive with cast aluminum. Quality requirements will have to be defined up front, which should lead to a better understanding of the product cost.

Mr. Samuel described a number of components made by Dow-UT:

- The first was a missile strongback (p. E-79). This part, delivered in 16 weeks from customer contract, was made using a steel tool. As an aside, Mr. Samuel remarked that "tools don't have to cost what they cost . . . we let them cost what they cost." He emphasized that "tool quality is part quality."
- A tactical munitions dispenser (not shown) was part of an AF demonstration/ validation program. Dow-UT fabricated a bulkhead and a tail cone from sheet molding compound.
- The TSSAM engine module of a cruise missile, shown on p. E-80, was fabricated using 1985 technology. The baseline component was an investment casting for which thin walls were an issue. The component, which consists of panels, rib stiffeners, and frame pieces, weighed 31 pounds (35 pounds with the cover). Its size is 3.5 feet (width) by 4.5 feet (length). Carbon AS4 fibers were used for the reinforcement. According to Mr. Samuel, "beautiful preforms" were made by Textile Technologies

although making such large preforms was an issue.[30] Some problems with the composite bulk factor were observed.

- The TSSAM fins were initially viewed as simple but, in reality, were not. The horizontal fins run along the long sides of the graphite torque box shown on p. E-81. The hollow areas were reinforced with Kevlar.
- Over 1,800 6-pack dispensers (not shown) were delivered for the Tomahawk cruise missile. The piece, which weighs about 8 pounds, is about 3.5 feet in width with mostly Kevlar foam with an inner and outer layer of graphite-reinforced composite. In response to a question from Gray Fowler, Mr. Samuel indicated the foam was probably cut by hand. The foam is a Dow product. It is not desirable for the foam to become frangible. No bond between the composite and foam is assumed in the structural analysis, so it was not looked for in inspection.

At this point in the discussion, LtCol Obal inquired about the decision-making process with respect to materials and processes. Mr. Samuel replied that Dow-UT was privy to decisions, but they were mostly in the position of convincing the primes to use RTM. He observed that getting a part to a customer quickly—something that can be touched and tested—makes the user more comfortable. Rapid prototyping makes this feasible. In response to another question from LtCol Obal, Mr. Samuel indicated that the cost is a major driver. Customers do spend time in the plant, but that usually happens later, once the decision has been made. Dow-UT generally provides up-front technical support to the primes. Mr. Samuel thought preform technology was critical, noting that at Dow-UT most people involved in structural analysis are also involved in making preforms. The speaker also believed that DoD should rely on today's process—a baseline, qualified process—using qualified materials. The primary issue is cost. He agreed that material costs are high; however, once a critical manufacturing mass has been established, a few key suppliers will be able to focus on particular technology areas. RTM represents a niche area of composites and, though growing, it probably will not reach the size of the prepreg-based product market. LtCol Obal then asked what was necessary to get off the baseline. When Mr. Samuel responded with a question—why?—LtCol Obal indicated that further cost reduction was necessary. Mr. Samuel suggested that cost reductions will probably result from evolutionary changes to in-house infrastructure (e.g., automate where it makes sense). Current market forces do not warrant more than such slow changes.

30 The preform technology was changed for the TSSAM munitions modules, not shown.

Mr. Samuel continued with a description of parts being considered for the F-22 and other aircraft. There are 250 parts under consideration for the F-22, a total of about 550 pounds of structure. Essentially, all these components are primary structure.

- The first was a 9-foot long sinewave spar (p. E-82). This curved part was fabricated using BMI composites.

LtCol Obal asked how components are selected for RTM. Mr. Samuel replied that the decision was based on a systems trade. Other factors to consider, particularly for primary structure, are an ability to hold tolerances (to avoid shimming) and wall thicknesses (important for fasteners). Issues such as these affect labor costs in assembly.

- A fuselage frame piece is shown on p. E-83.
- The engine inlet case for the JTDE program (for the F-119 engine) is shown on page E-84. This complicated structure consists of 19 hollow spokes attached to a ring. Two of these were fabricated, one for test, one for the engine mount. The key for this part is understanding preforms in terms of the bulk factor and stray fibers.
- The engine fan spacer, on page E-85, is being made at the rate of 6 per day for the Boeing 777 aircraft engine. Dow-UT is also making a fan cowl support cantilever structure (not shown) for the engine nacelle. It is about 5 feet long and 19 inches across.
- Part of the Advanced Ducted Propeller (ADP) fan exit case (1/10 of the ring) is shown on p. E-86. This part is about 4 feet tall and weighs 45 pounds.

The discussion moved toward challenges and issues associated with RTM. Mr. Samuel thought that two of the challenges to achieving high quality, particularly for primary structure, were fiber waviness and resin richness. He also stated that quality levels needs to be defined up front in the form of acceptance criteria. Quality levels are especially important from a subcontractor's perspective. Dow-UT is using tackified broadgoods for their preforms. The fabrics are held together with binders. There are issues associated with the binder. It is desirable for the binder to be chemically like the resin, something which is not always possible. Dow-UT uses three different binders: PT500 with PR500, one for BMIs, and one for "plain vanilla" epoxies. The binder, in essence, allows shaping of preforms. Mr. Samuel noted that RTM is less expensive because the preform does not have tack. A heat set is used to hold the fibers in place. Dr. Parnas inquired about preform fit in the tool. Mr. Samuel replied that once the part is in production, the preform fits in the tool every time. This may not be the case during the initial phase. He remarked that the preform tool is relatively inexpensive. Dow-UT has extensive material data for IM6-

reinforced PR500 and IM6-reinforced 5250-4 RTM BMI composites.[31] Mr. Samuel indicated that, as a subcontractor, Dow-UT does not take prepreg supplier data at face value. The company will believe the basic material property data if the supplier has done something to qualify the process, but he observed that design allowables are a different class of data. Mr. Samuel thought that the industry people should get together and agree on a couple of fiber architectures for such data. Dow-UT uses IM-type fibers and AS4 graphite fibers as well as glass fibers. In response to a question, Mr. Samuel said that the preform is inspected. Final inspection checks whether the tool closes. Dr. Parnas mentioned that when the preform distorts, as it does in the mold during closing, the permeability changes. The permeability also would change with the addition of other devices and inserts. Therefore, modeling and measuring flow behavior in the distorted and undistorted condition is important. Dow-UT does have a flow model program that was developed in-house. Its primary purpose is to help the tool designer; however, it can be used to simulate flaws and other potential problems. Mr. Samuel indicated that sensors are not used in the process. LtCol Obal commented that if one wanted to embed other devices and so forth having special temperature limitations, some higher fidelity knowledge of local temperatures and other conditions would be important. Mr. Samuel replied that it would not take government investment for such developments to occur. If Dow-UT saw this as a business opportunity, they would do it on their own, using simulation software first. In response to an inquiry, Mr. Samuel indicated that Dow-UT has not embedded fiber optics yet.

Mr. Samuel showed several photos of the factory floor and relevant equipment. The photo on page E-87 shows the application of tackifier (powder form) to the broad-goods. Preform cutting equipment is shown on page E-88. It results in an essentially numerically controlled (NC) shape. Dow-UT relies on robotic "pick and place" technology to move the cut piece and maintain fiber alignment. The length capability is 11 feet. The tools are large and heavy because of the large size of the parts; therefore, Dow-UT designed a flexible molding cell (p. E-89) A truck runs back and forth on a rail to carry tools from one station to the another. All the tools have common end fittings for resin lines, heating oil lines, electrical connections, and so forth. Mr. Samuel indicated that the initial parts are measured ad nauseum (p. E-90). He also observed that tools are very carefully inspected; inspections of part dimensions are required by their customers.

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31 The PR500 data were developed jointly with 3M. The RTM BMI data were developed with Dow-UT funds.

Mr. Samuel concluded by saying that RTM components can be mechanically equivalent to parts made with prepreg, especially if high performance resins are used. Control by detailed and rigid process specifications should make the customer more comfortable; if not, Dow-UT changes the process specification to increase the comfort level. In response to a question about other issues Mr. Samuel indicated that fastener installation was still an issue. He did not think RTM would be competitive with cast aluminum because industry would probably not be willing to pay for the increased performance achievable with the RTM process.

F. MATCHED METAL NET-SHAPE MOLDING, SPARTA/DR TECHNOLOGIES, GARY WONACOTT

Gary Wonacott described activities supported by BMDO to develop the MMNM process for fabrication of interceptor KKV structures. He mentioned the first structure fabricated by SPARTA—the Exo-Atmospheric Re-entry Interceptor System (ERIS)—which exceeded the structural dynamic performance of the baseline structure at substantially lower weight but, in the end, was more expensive. This high cost led to an increased emphasis on developing faster, more reproducible fabrication techniques for missile structures, reducing part count, and eliminating secondary operations where possible, all to reduce cost (p. E-93). Achieving a lower cost design based on the identified attributes requires a concurrent engineering approach involving prime contractors, fabricators, and materials suppliers. ProEngineer solid modeling provides a common database that keeps the project team members up-to-date throughout the product development cycle. This modeling tool, enabling the design of complex molds/tooling for closed mold processes, was not available to the composite designer 10 years ago. Mr. Wonacott emphasized the necessity for inserting composites early in the product development cycle through rapid prototyping because reaching a composite design early in the design cycle saves product development costs. He also observed that the composite part needed to be the same cost as aluminum. Rapid prototyping also allows for quick changes to existing tooling designs. According to Mr. Wonacott, 6 to 12 weeks is typical for turnaround time from the order. The goal of rapid prototyping is to cut that time in half. Process verification is another critical feature leading to increased acceptance of composites by the user community. SPARTA has verified that the MMNM tooling results in an extremely reproducible process through statistical process control (mostly through dimensional measurements). Studies of the science behind the process allow quantification and correlation of process parameters with composite quality (e.g., surface finish, void content, mechanical properties, and so

forth). While the existing team knows how to make parts, Mr. Wonacott thought that work had to be done to understand and quantify conditions in the mold during tool closure and cure.

Mr. Wonacott next described process issues associated with tooling, part lay-up, and part curing and de-molding (p. E-94). For tooling, having mold design flexibility to handle various types and quantities of resins and fibers is desirable. At the same time, rigid tool designs and materials to withstand high mold pressures are desired. Uniform heating and cooling throughout the mold (or even controlled heating and cooling where they are needed in the mold) is another issue that could be addressed through automation during the tool design process.

Complex molds require fairly long lead times. Mr. Wonacott observed that there "is such a thing as overkill." A company does not want the complexity of the tool to increase costs substantially. Mold maintenance costs could be significant, particularly with multiple molds. Companies would like to reduce tool turnaround time. Mold sizes are pretty much limited by part complexity. Less complex tools are generally better for large part sizes. Part lay-up represents about 50 percent of the cost because of the long lay-up time and high labor content. Although tool opening and closing can be automated, most will agree that fabricating precision structures with complex, geometric shapes is limited to hand lay-up. Other issues include methods to hold cores and other noncomposite inserts in place during the molding process and debulking of complex parts (e.g., box edges and corners). Mr. Wonacott commented that in-process monitoring may only be cost-effective for very high-value components. Much damage can be introduced in a component when trying to remove it from the tool. More gentle, rapid methods need to be developed.

Mr. Wonacott provided a few examples of complex components that have been fabricated using the MMNM process. The first is the highly loaded box structure shown on page E-95. This structure was fabricated in collaboration with Raytheon. He indicated that 40 to 50 percent of the cost went into making the interior rib members, which are conformal to thermal batteries. These ribs were co-cured to the face sheets, which contained integral fastener inserts. A foam sandwich material also was integrated into the face sheets to reduce weight.[32] High strength lugs, capable of transmitting primary loads, were also integral to the box. Dr. Ho asked about debulking. Mr. Wonacott replied that

[32] A 56-percent weight reduction was achieved for the composite component (4.8 pounds) over the baseline machined aluminum component (10.8 pounds).

debulking is required after every two or three plies and again mentioned the difficulty of debulking complex parts. The baseline machined aluminum component cost $3,000. The cost for the composite component was projected to be approximately $2,700. Mr. Woncaott pointed out that comparing baseline metal and replacement composite component costs is difficult. Another fabricated component was a generic exo-KKV structure (p. E-96). This component was unusual because it incorporated passive damping in the form of a visco-elastic material into the structure. SPARTA also has fabricated components containing coated fibers to handle electrical requirements, high thermal conductivity fibers to handle thermal loads, and coated fibers/particulate/sheets to handle shielding. The ability to fabricate these multi-functional structures in essentially a single step implies that structures with a metal-like performance may be achievable at lower cost than if the capability was added in a secondary step. A primary concern with achieving multi-functionality is how to do it without creating some other performance penalty such as degradation of the component's structural/load-bearing capability. Performance verification will be critical to increasing the application of technologies like these.

Mr. Wonacott identified several issues associated with materials and support. In general, prepregs were developed for autoclave processes, not for MMNM. The resin formulations are not ideal with respect to resin flow. To reduce cost, the amount of time in the mold at temperature and/or pressure needs to be reduced. Another wish is for material suppliers to hold tighter, more consistent tolerances on prepregs. He mentioned that SPARTA only performs receiving tests as specified by the customer, so they need to be able to rely on data provided by the supplier. In addition, they would like prepreg suppliers to be able to produce prototype quantities of material in a shorter period of time, noting that the two "tall poles" of support issues are tool design and fabrication and material delivery time. Longer shelf lives and longer certification times also are desired. Fabricators end up having to recertify material after it passes the "expiration date." A final concern is the lack of a common basis to compare the "same materials" from vendor-to-vendor.

The schematic on page E-98 illustrates how closed mold manufacturing can be integrated in a product development cycle. Mr. Wonacott mentioned that fabricators should be consultants to prime contractors early-on to fix the process. During the Demonstration/Validation (Dem/Val) phase, a few test parts and subassemblies would be fabricated using low cost tooling and then tested. During EMD, low rate initial production (LRIP), and full-scale production, 30 to 50 parts, 500 to 1,000 parts, and 5,000 to 10,000 parts,

respectively, would be fabricated. Increasing the production quantity justifies further integration of subassemblies (part count reduction) and other inserts and functions. The particular component shown was built for the Hughes Ground-Based Interceptor program. Mr. Wonacott mentioned that a SPARTA person was onsite at Hughes for 6 weeks to develop the composite design. SPARTA is fabricating five components for the Javelin tactical missile, now in LRIP (p. E-99). These components are fully qualified through > 50 live firings to verify performance. By the end of 1995, more than 8,720 parts will have been fabricated. These five composite missile components will provide an extensive database and field-use experience with composites.

According to Mr. Wonacott, the three primary concerns are tooling costs for early development phases, process science, and field experience (p. E-101). Future technology developments should focus on process science to increase the understanding of what happens to prepreg in a geometrically complex tool; development and demonstration of multi-functional structures with improved performance and quality; and integrated structures.

V. DISCUSSION AND CONCLUSIONS

A. DISCUSSION

LtCol Obal began the final discussion session by commenting that, in his view, the lessons learned from the aircraft community for autoclave processing also apply to closed mold processing. He did, however, note the special concerns of the mold/tooling community. He asked a rhetorical question about the availability of base materials, preforms, and prepregs, wondering if the present system of making materials available was acceptable as long as the customer is satisfied through some set of procedures. Mohan Aswani agreed and observed that agreeing on what constitutes qualified materials is difficult since each prime contractor has his own set of criteria to qualify base materials and parts. There appears to be no motivation for a supplier to qualify materials and parts, although one of the attendees noted that if a material is qualified by one prime, there is an advantage in going to another prime with the same material. Allen Samuel mentioned there has never been common sense in industry. There is little to no trust.

LtCol Obal then asked if a set of basic parameters that could be evaluated within certain tolerances would be too much to ask, a question to which an attendee replied yes. Jerry Sundsrud indicated that the data often cannot be obtained because someone else paid for it. The fact that the Services have different requirements was again identified. These requirements should be the same, a situation which is not likely to occur either, according to several attendees. Allen Samuel remarked on the differences between commercial and military testing, an additional cost factor that will be important for those companies trying to serve both markets. Jerry Sundsrud observed that the trend for prime contractors is to band together to select resins and fibers for test. In this way, they can obtain the data they want. Bill Fossey stated, however, that Raytheon was looking for design data, not material property data. While the methods to determine design allowables are somewhat fixed—A- or B-basis allowables are based on statistical procedures—the way they are applied within a given company differs to a significant degree. John Stubstad noted the difficulty in getting agreement on what systems from which to obtain data.

One suggestion for what to do next addressed the issue that the right resin systems do not exist. Mohan Aswani thought it would be difficult for resin suppliers to react to this suggestion because the demand is so low. He believed that two or three resins with multiple uses should be selected and used. These resins could be evaluated by building and testing parts and comparing test results with modeled performance predictions. Using the PR500 as an example, Steve Hackett answered the question about what motivates a new resin. This resin was originally developed in the 1980's as a prepreg resin. It happened to have the right flow and process characteristics for RTM. 3M saw these characteristics as an opportunity for an earlier market so it was introduced in 1989 and has since been qualified for the Boeing 777. To develop a new resin, 3M would have to see a market, basically a real customer need. Steve observed that Dow, Ciba, and Shell may have a different view because, unlike 3M, they are geared more to the extremely large volume automotive market. He estimated that the cost for developing a new resin system could range into the hundreds of thousands for R&D and testing. Process development and scale-up could push that figure much higher. Richard Parnas asked about anticipated testing costs and their effect on resin development. Steve Hackett replied that he did not have a figure for testing costs, but that these costs would definitely affect the decision to develop a new resin. Mr. Sundsrud commented that the RTM resin should be able to meet the properties on the data sheet if it is properly processed.

In this sense, it is important to qualify the process and testing procedures. Jerry Sutton stated that for Federal Aviation Administration (FAA) certification for commercial aircraft, the first 10 composite parts must be C-scanned. The next 15 parts are A-scanned, followed by A-scanning of the forward nose. After this scanning process is completed, no parts need to be scanned. In the end, most agreed that if an order is placed to buy some products the problem of qualification will take care of itself. LtCol Obal agreed, observing that if industry self-adjusts without government help, it is better, at least in specific industries. Milt Anderson asked about the utility of Mil Handbook 17. The response seemed to be that the materials are changing so rapidly that it cannot keep up.[1] Les Kramer expected big changes to arise from new procurement rules, and he did think a database would be necessary. He believed that vendors can only be asked to supply data on uni-directional and standard lay-ups. The primes should test everything else. Bill Fossey pointed out that if funds were not available for this testing, no composites will

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1 The original idea was that Mil Handbook 17 would contain data for a generic composite formulation, but there is not really any such thing.

be used. The part will be metal. The prime would have to provide design analysis and the material property and component test data to back it up. Additional costs would be incurred with flight tests, with the amount depending on how much of the flight envelope required evaluation. He concluded that Raytheon would only use composites where they offered tremendous costs savings or if the customer required it from a performance point of view (e.g., increased range). LtCol Obal observed that a prime can get more "bang for the buck" by getting composites people involved early in the program. Another attendee remarked that it is difficult to influence the structural design unless it is done from the beginning. Electronics and avionics are usually the primary features that affect the design, and the structure is driven by the volume necessary to contain those things. LtCol Obal thought that it would be difficult for hypersonic missiles to meet the aerodynamic and heating performance requirements without composites. Bill Fossey emphasized that there had to be motivation to use the composites, noting that standard materials have been successful so far (the "if it ain't broke don't fix it" approach). To move off these standard materials requires that the primes, subcontractors, and government work together.[2] Joel Zuieback suggested that since composites were perceived as high risk areas, the government should fund parallel development programs. LtCol Obal then asked if primes would entertain using composites in existing systems if advances in part count reduction and weight savings could be achieved. The response was probably not, although specific components might be considered if the existing component had a service problem. In general, using composites in new systems is a better choice and more likely to be achieved. It was observed that the number of new programs coming down the line are limited. The AIM-9X, advanced Sidewinder missile, was mentioned as a possibility. Gary Wonacott asked if there were any preplanned production improvements for this system. Bill Fossey replied that there were not at present and that structural upgrades would only be considered in desperation. However, he did think a new rocket motor might be considered. He also remarked that most older missile systems are overdesigned. Current designs are much tighter and closer to the margin. Les Kramer commented that the move to composites at Lockheed Martin-Orlando has been slow because of cost issues, a perception that the materials are not mature, and a general lack of comfort with composites. These comments closed out the final discussion.

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2 Mr. Fossey observed that selling composites to the government program offices is not any easier than selling within their own company.

B. SUMMARY OF ISSUES AND LESSONS LEARNED[3]

Everyone agreed that fabricators and materials suppliers should be involved in development programs with prime contractors from the beginning. The importance of defining quality up front was mentioned as critical to successful implementation of composites. It was also quite clear from the discussion that "Black Aluminum" designs are not cost-effective and that components fabricated through closed mold manufacturing must be cost-competitive with baseline aluminum components.

1. Designers

The designers/end users participating in the workshop identified some "rules" for use of composites in real systems:

- In general, the prime contractors rely heavily on previous experience. If the designers have little or no experience with the materials, the materials will not be considered in/evaluated for the design.
- Mission requirements, costs, and schedules are important factors in the selection of composites for a real system. If the materials cannot offer a demonstrable performance improvement at a reasonable cost and in a reasonable time, they will not be considered.
- Limited initial program quantities drive nonrecurring costs. These costs could be too high for composites to be considered.
- Limited development spans require mature materials and processes. Advanced composites often do not fall into this category. The ability to get a part to a customer in a relatively short period of time, such as by rapid prototyping, can increase user confidence in the material and process.
- Customer configuration management requirements promote no-change policies, which makes it difficult to insert composites after the fact.
- The inability of composites to meet development schedules is attributed partly to a lack of user understanding of the material and its interactions with/effects on the rest of the system and the perceived inability of components to pass qualification tests.
- Benefits of part count reduction need to be quantified.

3 Product liability, although not discussed in great detail, was clearly an issue for all three groups.

- Several speakers noted the need for an integrated team approach and for risk mitigation activities to address technical issues associated with the use of composites.

They also identified several issues and concerns associated with the use of composites for missile structures, in general, and with the use of closed mold processing for composite missile components.

- The fact that the materials and processes are always changing represents a significant challenge to the user in evaluating and qualifying the material. This constant flux also affects material availability/maturity and quality.
- There is a material storage problem (physical space, time, and cost) for uncured composite materials, particularly for the epoxy-based systems.
- Untried manufacturing technologies raise concerns and increase program risk. There is a longer learning curve with such processes. Most program development schedules do not allow such processes to be used.
- Suppliers need to provide process documentation and proof of the process. They also should notify the user of process changes. Lot/component traceability also must be documented.
- There are concerns about reject rates, which can be high for some composite processes (partly a function of user experience). These high reject rates stem from inadequate part quality and lack of part-to-part reproducibility (e.g., variations in manufacturing tolerances, inconsistent properties, defects arising from secondary fabrication/manufacturing operations).
- Hand lay-up of the prepreg is the most expensive step in manufacturing composite components.
- Generally, users familiarize their manufacturing people with new technology at the component and subsystem level.
- Several of the primes expressed an interest in rapid prototyping to reduce cycle time, run design iterations, and check form and fit.
- The issues associated with maintenance and reparability also were mentioned, in particular, the number of assembly/disassembly cycles that may lead to increased damage of the structural components.

With respect to closed mold processing, most of the concerns were associated with tooling and methods used to integrate other functions into the composite.

- All of the users agreed that quality tooling was very critical for closed mold processes but decried the trial and error approach to tooling design. (They also

felt this trial and error approach applied to preform design and process development.)

- Amortizing tooling costs can be an issue depending on the tool material selected and the number of parts to be fabricated.
- Manufacturing methods to integrate thermal management, mounting rings/ flanges and secondary inserts, and so forth are not well developed.
- Geometric complexity is a particular issue in preform fabrication if the component is to be made in near net shape form. It may also be an issue for mold filling (e.g., design of gates and vents to allow the correct resin flow to all parts of the structure).

There was, not surprisingly, much discussion on the lack of material and design data.

- A primary difficulty facing users is a "not invented here" attitude about data, particularly for composites, since there is a lack of standardization. Most companies have proprietary databases, which they are unwilling to share.
- Little-to-no design allowables data are available, in particular missile-specific design data for the operational environment (e.g., dimensional stability at high temperature, heat transfer, material compatibility with fuel and fluids, damage tolerance, shock and vibration performance, load transfer at joints). Analytical models to support the design data also are not available.
- The importance of T&E of composite parts was emphasized although the costs associated with those activities were identified as an issue. Structural performance verification through full-scale ground and/or flight tests will go a long way toward increasing user confidence in the materials and processes.
- All agreed that a "Black Aluminum" design approach is not cost effective for composites.

2. Materials

a. Preforms

Issues associated with preform technology and lesson learned from the suppliers include the following:

- Preform reproducibility problems stem from variations in fiber volume fraction and from fiber waviness and geometrical tolerances.
- High modulus fibers are difficult to handle. Fraying is observed.

- Compatibility of the fiber sizing with post-weaving process steps is critical. If the sizing is not compatible, pores or undesirable reaction products that affect mechanical properties may form.
- There are limitations on the achievable fiber volume fraction in woven preforms. The theoretical maximum is 0.55 with certain types of weaves. (Achieving higher volume fractions by using compressible weaves may be possible.)
- Handleability of low-volume fraction preforms is an issue since the preform is very loose and cannot support itself.
- Binders are often required to hold fibers in place during processing. These binders also must be compatible with post-weaving processes.
- There may be a preform thickness maximum for a given weave construction because there is only a one-shot impregnation cycle.
- There are little mechanical property data available on different weave types. This problem is exacerbated by the wide range of fiber orientations and volume fractions that can be achieved.
- Not all weave constructions are suitable for all closed mold processes.

b. Resins

Issues associated with the resins and lessons learned by the suppliers include the following:

- It is difficult to achieve real-time resin mixing if using a two-part resin system. There are also equipment clean-up and worker safety issues associated with two-part resin systems. These concerns have led to the development of single-part resins.
- The lack of high-performance resins for RTM was noted although it is not clear there would be an adequate market right now to warrant the necessary R&D for such resins.
- There is a limited database on existing "high performance" resins.
- There is a general lack of working knowledge of the RTM process, at least in the aerospace industry.
- The importance of accurate material and process specifications from users was identified although the suppliers noted a wide variability among user specifications. This variability makes it more difficult (and expensive) to qualify materials and processes.
- EPA requirements discourage the development of new resins.

c. Prepregs

From the discussion of prepreg suppliers, it was obvious that there is significant flux in the industry. Mergers, sell-outs, dropped product lines, and plant closings are a regular, almost monthly, occurrence. This situation is attributed in large part to shrinking defense budgets and the continuing high process costs associated with tooling, fabrication, and assembly of composite parts.

- Prepreg suppliers are faced with increasing competition from abroad (i.e., Toray, the primary supplier to Boeing for the 777).
- The domestic companies generally have production overcapacity.

3. Part Fabricators

The fabricators identified several concerns associated with tooling design and fabrication, perhaps the most critical factor in achieving high-quality parts. Lessons learned in the fabrication of particular components also were highlighted.

- Success or failure of component fabrication through closed mold processes relies heavily on tool design and requirements. Particular features to address in the design relate to uniform/controlled heating and cooling through the mold and thermal expansion mismatch arising from dissimilar tool materials. Mold-filling simulations were thought to be one approach to address some aspects of tool design (number and location of vents and gates).
- Selecting the correct tool material is essential. The selection will depend on the schedule, available funds, and the number of parts to be fabricated. Critical properties include strength, stiffness to prevent deflection during the cure cycle, and thermal properties such as thermal conductivity (mold heating and cooling) and thermal expansion (CTE mismatch between different tool materials and between tool and composite).
- The lead time for complex molds is quite long (on the order of months depending on the level of complexity and the tool material).
- The time required to prepare the tool and the labor costs associated with this preparation are an issue. One way to reduce tool preparation time is to reduce the number of vents. (Note that the ability to achieve reduced tool preparation time depends somewhat on the shape and size of the part being fabricated.)
- Tool ejector systems (including release coatings) to allow easy removal of the part from the mold and to reduce damage are desirable.
- Having duplicate part tooling available to fabricate preforms is helpful.

Specific processing issues identified by the fabricators appeared to be somewhat dependent on the part being fabricated.

- Closed mold manufacturing processes are appropriate for particular classes of components, but not for everything.
- Part reproducibility (tolerance control, surface finish, and so forth) is an issue.
- In-process monitoring should be done only if necessary and if the parts are expensive enough to warrant the capital investment.
- Fabricators have experienced problems in manufacturing components from dissimilar materials, for example, foam cores with composite skins.
- Methods to hold cores and other noncomposite inserts in place during resin injection are inadequate.
- The ability to fabricate preforms reproducibly is critical to achieving good quality parts.
- Components fabricated with 3-D preforms have exhibited high resin shrinkage and poor surface quality.
- The bulk factor associated with uncured composites, especially prepregs, is more of a concern in the matched metal net-shape molding process. It particularly affects tool design and tool closing. If not handled properly, damage can occur in the cured composite (broken, crushed, or misaligned fibers, and so forth).
- Important variables affecting the resin transfer molding process include the fiber volume fraction and type of weave, temperature, pressure, and component geometry.
- Fiber motion and waviness are particular problems in components fabricated from low fiber volume fraction preforms through RTM. Resin richness also is observed, but it depends on the specific preform weave.
- Secondary bonding of composites to other materials can be difficult. Special surface preparation techniques may be required.

The fabricators also noted some issues and discussed lessons learned with respect to materials, including resins, preforms, and prepregs, and relevant data.

- Long material delivery times are somewhat more common for advanced composite materials because of a lack of material availability/maturity. This, in turn, affects the ability of fabricators to deliver parts to the user in an acceptable time frame.
- Properties of the composite raw materials are important, especially resin properties. One-part/no-mix, low viscosity resins with long pot life are most

desirable. Some current resin formulations are not ideal with respect to desired flow characteristics.

- Conformable fabrics and other woven reinforcements are most often used and appear to be more easily characterized that other preforms. Properties of braided preforms are difficult to characterize and are, therefore, considered less desirable by some.
- Prepreg variability was identified as a problem by some fabricators; thus, there was a suggestion for tighter, more consistent specifications.
- The lack of a common basis to compare nominally the "same" composite materials from vendor to vendor was identified as a problem.
- Since a "one shot missile system is different than a man-rated aircraft" it does not make sense for missile component fabricators to have to supply B-basis design allowables.

C. WORKSHOP RECOMMENDATIONS

The missile community appears to be interested in increasing the use of composites in general if the components can show a demonstrable performance improvement and can be manufactured at reasonable costs (comparable or better than those of similar aluminum components) and delivered on schedule. Closed mold manufacturing approaches such as RTM and MMNM are one way to address these concerns. However, as noted previously, some issues must be resolved before these materials and manufacturing approaches will see more widespread use. The following sections address specific recommendations by the workshop participants to address these issues.

1. General Programs

- Fund technology programs involving primes and suppliers in time for program consideration.
- Make producibility a contract requirement with each contract phase and allow for producibility "block upgrades."
- Fund parallel development programs, particularly since composites are perceived as high risk.

2. Design and Analysis

Recommendations in this category apply to composites in general and to composites fabricated by closed mold manufacturing processes.

- Establish general design guidelines for using composites in missile components and structures.
- Define design approaches for integration of functions other than load-carrying ability (e.g., electrical shielding, damping, thermal protection) and of other features (e.g., metal inserts, fasteners) into composite missile components.
- Further develop structural analytical techniques and models including, for example, optimization codes for minimum missile weight, nonstructural design standards for composites, analytical codes for multi-component anisotropic material systems, determination of empirical design relationships, and structural modeling during transient environmental conditions. The last item was specifically identified as a critical need.
- Investigate design approaches to eliminate mechanical fasteners.
- Develop 3-D models for resin flow in complex fiber preforms.

3. Data

- Establish a standard composite material database available to all users (e.g., a standard Tri-Service material database with agreement among the services at a minimum)
- Establish design allowables for closed mold composites based on several fiber architectures agreed upon by industry representatives.
- Standardize data development methods (e.g., ensure that standard test types and methods are used to evaluate/qualify materials and processes).

4. Materials

- Develop low-cost preform manufacturing methods and improve preform tolerances.
- Develop new binders and binder application methods for preforms.
- Optimize existing RTM resins and develop an RTM resin with high temperature capability.
- Make prototype materials available within a short period of time with longer shelf lives and longer certification times.

5. Manufacturing

- Establish a baseline qualified RTM process by relying on the current process and by using qualified materials.

- Develop a critical manufacturing mass and not a missile-specific manufacturing technology.
- Consider development of agile/low rate manufacturing processes especially for versatile tooling.
- Develop and demonstrate processing methods to integrate other functions and features into composites. Include the testing of such integrated/multi-functional structures.
- Develop repair systems and techniques.
- Focus on process science to increase the understanding of what happens to prepreg in a geometrically complex tool. Include the development of in-process control methods and appropriate sensors if necessary
- Investigate tool material alternatives for steel to reduce costs and delivery time.
- Develop adaptable, easily repaired tooling; durable, low-cost tooling for low volume production; and near net-shape tooling to reduce machining, part count, and joining.
- Standardize tooling gating and venting concepts.

D. FINAL RECOMMENDATIONS FOR BMDO

The current, shrinking budget environment does not permit the DoD to support all the recommendations described above.[4] Which ones are most sensible?

From a programmatic perspective, the BMDO M&S office should continue to support technology programs involving component fabricators and those programs involving prime contractors and material suppliers. Support of parallel technology development programs is a logical approach, particularly since composites are typically perceived as high risk by the user community. These activities will help increase user familiarity with and confidence in the materials and processes and also will help address the technical issues associated with achieving good quality, consistent, reliable composite structures.

Another important topical area for BMDO to address is the development, demonstration, and test of multi-functional missile structures. Previous M&S projects have already addressed some of the design and manufacturing issues associated with integrating various devices and other features into load-bearing structures and testing their perform-

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4 Nor is it clear that the government should support all of these activities even if it was possible.

ance. This expertise can be extended to address specific features applicable to interceptor missile systems. These multi-functional structures may be able to improve missile system performance under the demanding dynamic and thermal conditions experienced in the operational environment.

As for other workshops, a major issue of concern to the designers is the lack of a statistical/design database for composites, in general, and for closed mold-processed composites, in particular. This workshop specifically identified a lack of missile-specific design data for the operational environment. One solution to obtain the data may be to support a group of companies—end users, material suppliers, and component fabricators—working together, perhaps in a "round robin" format, using agreed upon materials, designs, and test procedures. Commonality of test techniques will be a key factor in making such an effort successful. Relevant design data also could be obtained through well-instrumented ground and flight (preferable from a designer perspective) tests although costs for such tests can be very expensive. As a first step in this direction, requesting an end user definition of specific test data and materials (resins, fiber orientations, preform weave types, manufacturing processes, structural configurations, and so forth) of interest would be most useful. Any common responses could then be further evaluated before designing appropriate experiments and proceeding to actual tests.

GLOSSARY

3-D	three-dimensional
4-D	four-dimensional
5-D	five-dimensional
ACS	Attitude Control System
ADP	Advanced Ducted Propeller
AHIT	Advanced Hover Interceptor Test
AIWS	Advanced Interdiction Weapon System
ARL	Army Research Laboratory
ARPA	Advanced Research Projects Agency
ASAT	Anti-SATellite
BMDO	Ballistic Missile Defense Organization
BMI	bismaleimide
C/C	carbon/carbon
CAI	Compression After Impact
CLU	command launch unit
cps	centipoise
CTE	coefficient of thermal expansion
DACS	Divert Attitude Control System
DARRT/LEAP	Development of Advanced Risk Reduction Technology/ Lightweight Exo-Atmospheric Projectile
Dem/VAL	Demonstration/Validation
DoD	Department of Defense
DSC	differential scanning calorimetry
EFEX	Endoatmospheric Flight Experiment
EKV	Exo-atmospheric Kill Vehicle
EMD	Engineering and Manufacturing Development
EMI	electromagnetic interference
EPA	Environmental Protection Agency
ERIS	Exoatmospheric Re-entry Interceptor Structure
FAA	Federal Aviation Administration

FCR	free control radar
FEM	finite element modeling
FMI	Fiber Materials, Inc.
FY	fiscal year
GLC	gel permeation chromatography
GLCC	Great Lakes Composites Consortium
gm/m^2	gram per meter squared (check document)
HPLC	high performance liquid chromatography
HSCT	High-Speed Coil Transport
HVM	hypervelocity missile
IDA	Institute for Defense Analyses
IM	injection molding
in^2	square inch
IPOS	In-Process inspection Operation Schedule
IPT	integrated product team
IR	infrared
IRAD	internal research and development
IRBAS	infrared transparent Barium-Alumino-Silicate
IRS	infrared spectroscopy
ISO	International Standard Organization
JTDE	Joint Technology Demonstration Engine
KEW	Kinetic Energy Weapon
kg	kilogram
KHIT	KKV Hover Interceptor Test
KKV	kinetic kill vehicle
KV	kill vehicle
LCCW	Low Cost Composite Weapons
LDEF	Long Duration Exposure Facility
LM	Lockheed Martin
LMMSC	Lockheed Martin Missiles and Space Company
LRCSOW	Long-Range Conventional Stand-off Weapon
LRIP	low rate initial production
LV	Loral Vought
M&P	Materials and Process
M&S	Materials and Structures

MDA	McDonnell Douglas Aerospace
MDA	methylene dianiline
MERS	multi-element radiometer system
Mil	Military
MLRS	Multiple Launch Rocket System
MMNM	matched metal net-shaped molding
MMS	missile monitor system
MSOW	Modular Stand-off Weapon
N-D	N-dimensional
NASA	National Aeronautics and Space Administration
NC	numerically controlled
NDI	non-destructive inspection
NIST	National Institute of Standards and Technology
OEM	Original Equipment Manufacturer
P&W	Pratt & Whitney
PAC–3	Patriot Advanced Capability-3
PAES	poly-aryl-ether-sulfone
PAN	poly-acrylo-nitrile
PBI	polybenzemidazale
PC	personal computer
PCD	Process Control Document
PEEK	Poly-Ether-Ether-Ketone
PI	polymide
PPS	poly-phenylene sulfide
psi	pounds per square inch
QFD	quality function deployment
R&D	research and development
RDS	rheometric dynamic scanning
RFI	radio frequency interference
RTM	Resin Transfer Molding
SABIR FE	SpAce-Based InterceptoR Flight Experiment
SACMA	Suppliers of Advanced Composites Materials Association
SLA	stereo-lithography approach
SOP	Standard Operating Procedure

T&E	Test and Evaluation
T_g	transition temperature
THAAD	Theater High Altitude Area Defense
TI	Texas Instruments
TMD	Theater Missile Defense
TMDE	Tactical Munitions Dispenser Equipment
TPC	thermoplastic composite
TSSAM	Tri-Service Stand-off Attack Missile
USAF	United States Air Force
UV	ultraviolet

APPENDIX A

REVISED FINAL AGENDA

Revised Final Agenda

Workshop on Closed-Mold Manufacturing of High Performance Composite Missile Structures

Institute for Defense Analyses
2001 N. Beauregard St.
Room 118
May 15-16, 1995

Monday, May 15, 1995

	Topic	Speaker
8:30 am	Begin check-in, coffee & donuts, etc.	
8:50	Welcome	J.M. Sater, IDA
8:55	Introduction	LtCol M. Obal, BMDO
9:15	Why are we here?	J.M. Sater, IDA

I. Missile System Producers

Lockheed Missiles & Space (now Lockheed Martin Missiles & Space)	Tom Anderson
Loral Vought Systems	T. Ho
Break	
Martin Marietta-Orlando (now Lockheed Martin Electronics & Missiles)	Les Kramer
Hughes Missile Systems	Ross Ringwald
McDonnell Douglas Aerospace	Jerry Lehman
Lunch	
Raytheon	William Fossey, Jr.
Rockwell Aerospace/Rocketdyne	Richard Hilscher

II. Material Suppliers

Preform Technology	Fiber Materials Inc., Paul Martin
Resins for Closed Mold Processes	3M Aerospace, Jerry Sundsrud

	Resins for Closed Mold Processes	Ciba-Geigy, Andy Wang
	Recent Prepreg Supplier History	J.M. Sater, IDA
	Prepreg Technology	ICI Fiberite, J.M. Sater for Paul Schmitz

III. Parts Fabricators

	Resin Transfer Molding (RTM)	McDonnell Douglas Aerospace, Jerry Lehman

Tuesday, May 16, 1995

7:30 am	Coffee & donuts	

III. Parts Fabricators (contd)

8:00	RTM	Texas Instruments, Gray Fowler
NO SHOW	Matched Metal Net-shape Molding (MMNM)	Alliant Techsystems, Kay Dickerson
	RTM	Intellitec, Jerry Sutton
	Break	
	MMNM	Composites Horizons, Milton Anderson
	RTM	Dow-United Technologies Composite Products, Allen Samuel
NO SHOW	MMNM	Merlin Technologies, Walt Wilson
	MMNM	SPARTA/DR Technologies Joe Zuieback/Gary Wonacutt
	Lunch	
	Discussion & Closing Remarks	All

Workshop on Closed-Mold Manufacturing
of High Performance Composite Missile Structures

May 15-16, 1995

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APPENDIX B

OPTIONS AND POTENTIAL OPPORTUNITIES

Closed Mold Manufacturing of Composite Structures for BMDO

Options and Potential Opportunities

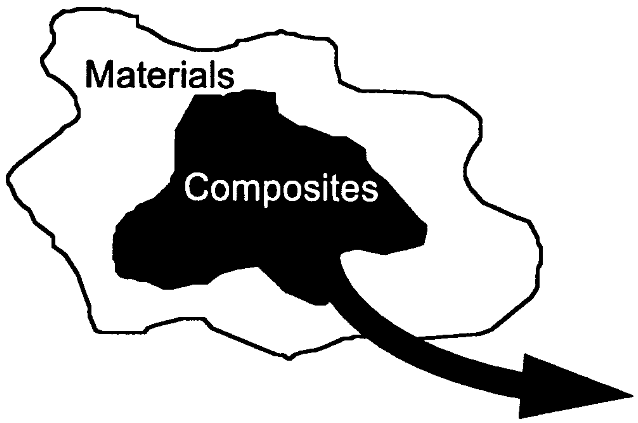
Workshop on Closed Mold Manufacturing
May 15-16, 1995

LtCol Michael Obal
Ballistic Missile Defense Organization
Materials and Structures Program

Closed Mold Manufacturing Technology

- BMDO has advanced the art of closed mold manufacturing to be cost competitive with metals for high performance interceptor structural components.
- This technology is conducive to manufacturing agility and cost effective production of multifunctional structures.
- This provides an opportunity to develop this technology for other DoD systems and specialized commercial products.

High Performance Composites



Lightweight, stiffness critical, multifunctional high performance composites

Matrix Materials

Carbon Fibers	Ceramic	Metal	Resin
Continuous	Highly specialized Extremely limited use	Highly specialized Extremely limited use	**Potential growth in general use**
Discontinuous	Well established	Limited growth	Well established

Continuous fiber resin matrix composites offer a potential growth in general applications for high performance structures.

Continuous Fiber Resin Matrix Composites Technology BMDO Investment Areas

Materials and process research	Composite design tool development	Manufacturing
Cost of Basic Materials	Cost of Design	Cost of Manufacture
<u>Mature capabilities</u>	<u>Mature capabilities</u>	<u>Maturity affected by industry demand</u>
		BMDO $

Industry reluctance to accept high performance composites is the lack of products demonstrating competitive cost of manufacturing.

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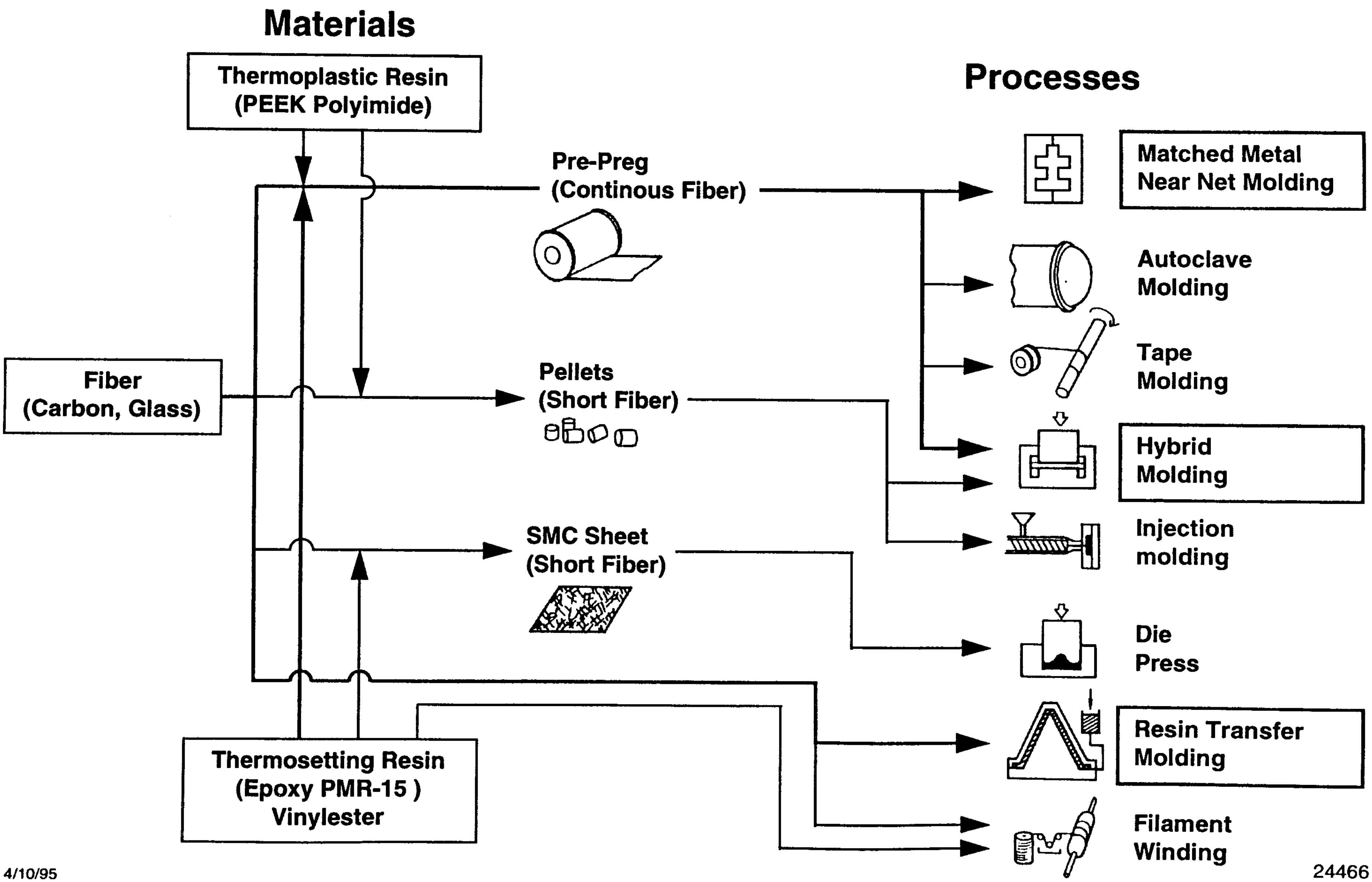
Resin Matrix Composite Manufacturing



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Closed Mold Fabrication Process

Closed Mold Fabrication Process Options

	Resin Transfer Molding	Matched Metal Net Molding
Description:	Produces dry fiber preform and subsequently injects resin into mold to fully infiltrate preform and cure	Uses prepreg precursor which is placed between two matched metal tools; tooling is closed and the prepreg is cured
Advantages:	Automated preform fabrication can satisfy 3-Sigma requirements; can produce larger components because of lack of tool mobility requirements	Can produce very complex shapes; can accommodate multifunctionality; can use a wide variety of resins (e.g., high temperature polymide)

BMDO Composite Technology Program

Time	Program Emphasis
FY 87 (Started)	**Engineering Requirements** • Extreme stiffness structures • Lightweight structures • Design tools development
	Manufacturing Methods Chosen • Match metal near net molding - interceptor components • Textile braiding - propulsion components
FY 90	**Multifunctional Requirements & Manufacturing Costs** • Manufacturing methods reexamined matched metal near net molding and textile braiding chosen
FY 94	**Increased Manufacturing Cost Reduction** • Multifunctional capability single step manufacturing • Closed mold automation • In situ NDI • Agile manufacturing • More complex braiding

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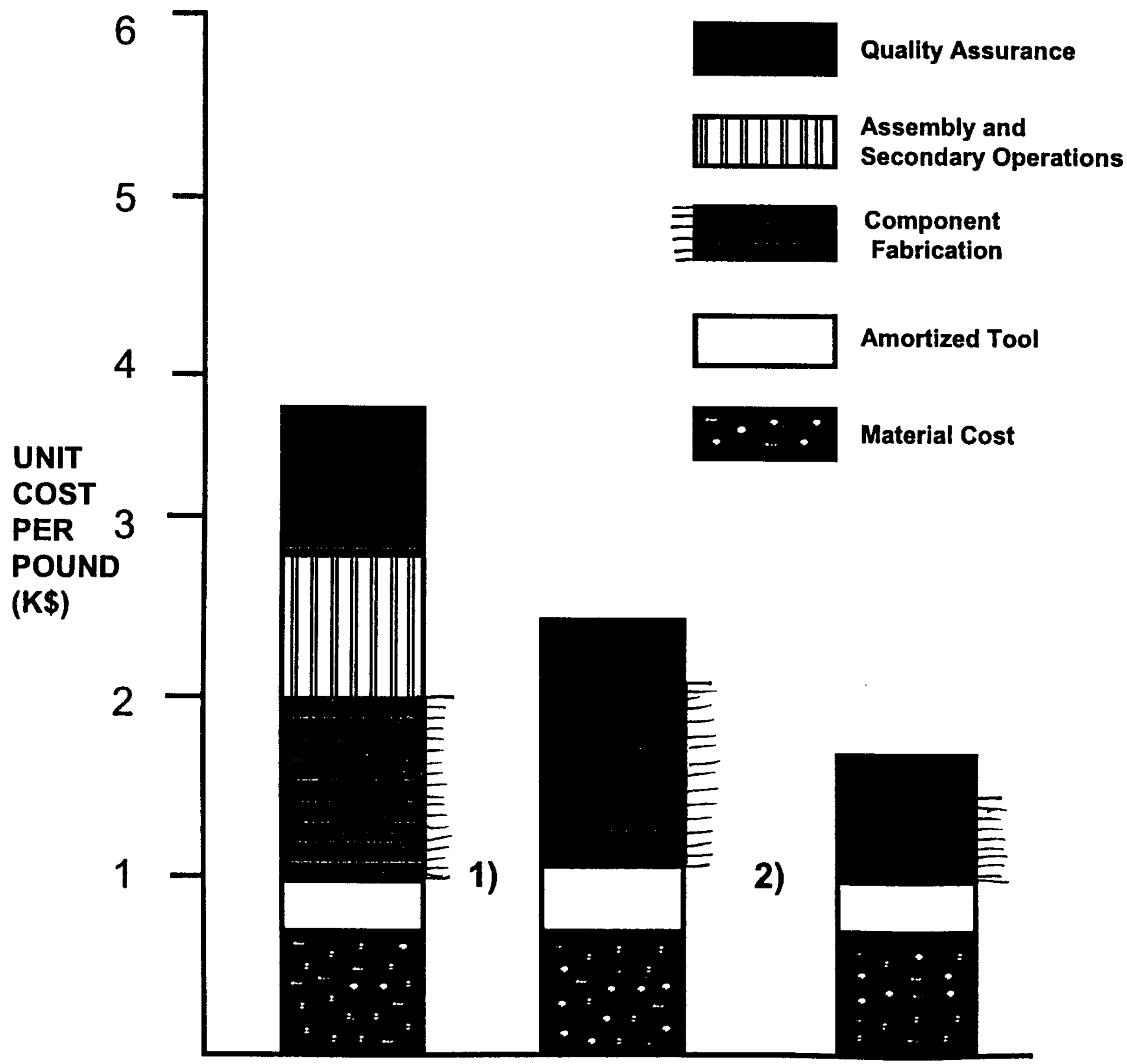
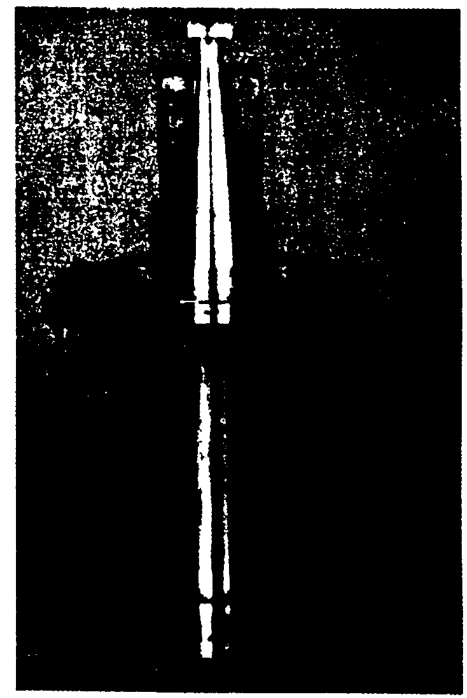
MANUAL AND AUTOMATED NET MOLDING OFFER COMPOSITE AIRFRAME COST REDUCTION POTENTIAL



1) Tool Costs Amortized over 500 Units
2) Tool Costs Amortized over 1000 Units

GENERIC AIRFRAME MOLD



- One Piece Net Molded Ultrahigh Modulus Graphite Fiber Thermoset Structure
- Tool Incorporates all Geometric Features of Structure (Penetrations, Inserts, Foam Sandwich Bulkheads)

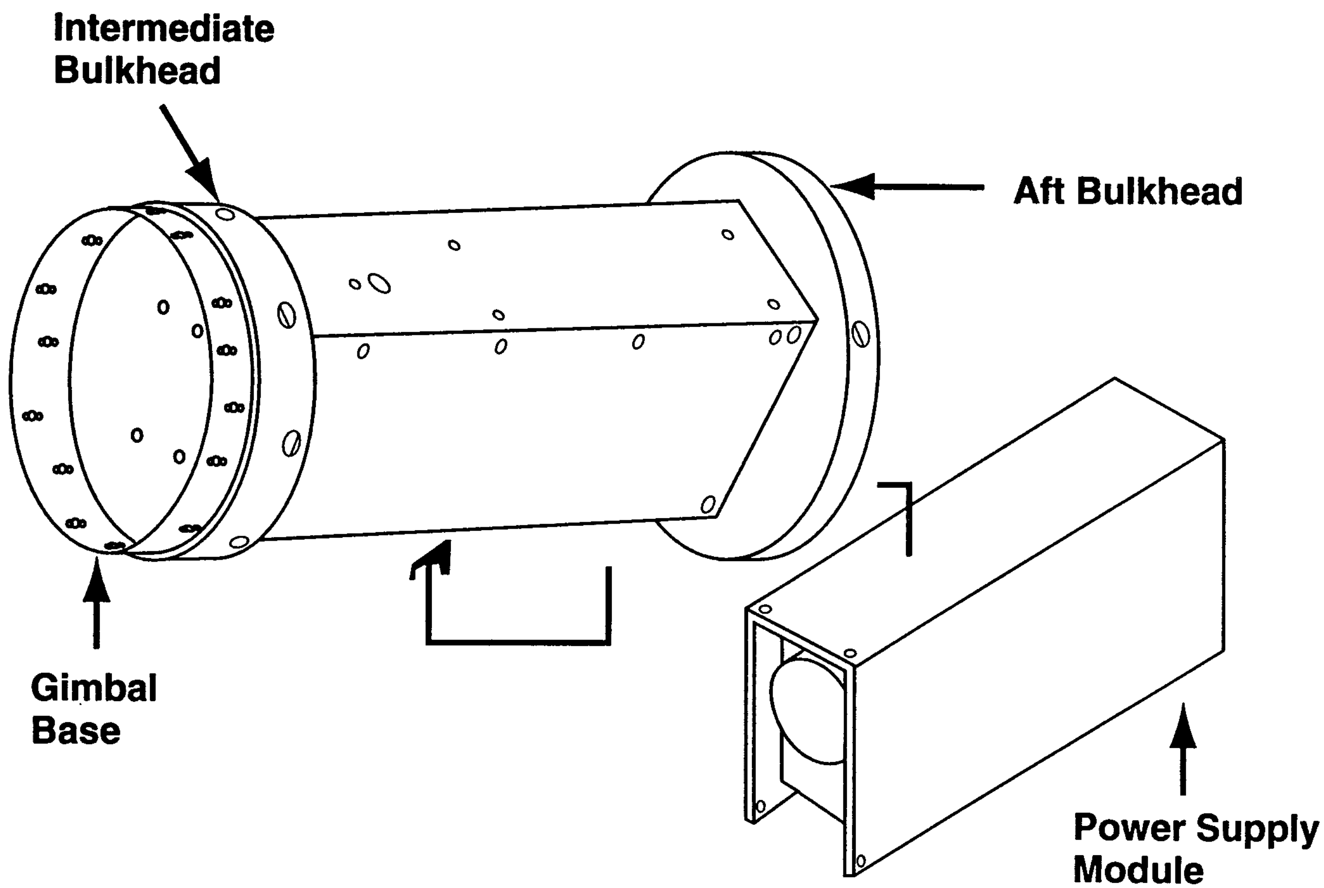
4/10/95

km10098

Advanced Type O Multi-Functional Structure Application

Missile Avionics Container

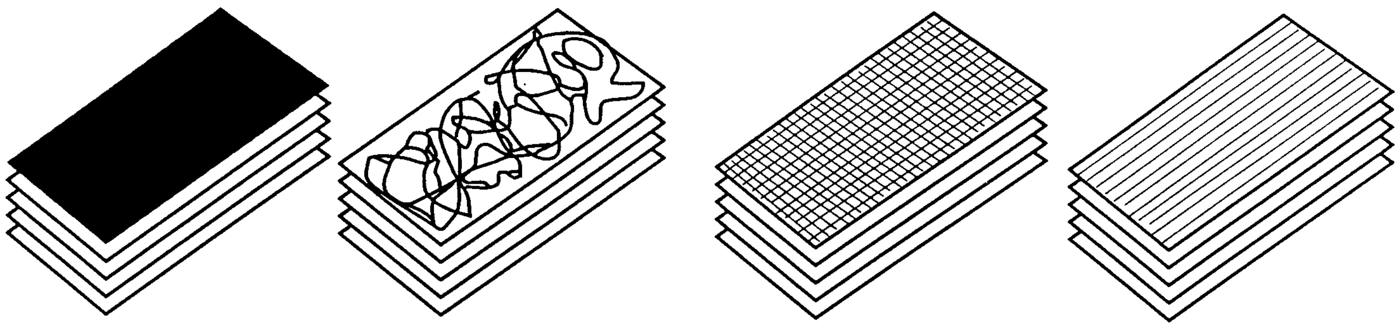
$M_O = L_{ST} \cap H$



Load-Bearing Composite with Thermal Control, EMI, and Ground-Plane Shielding

64055-003

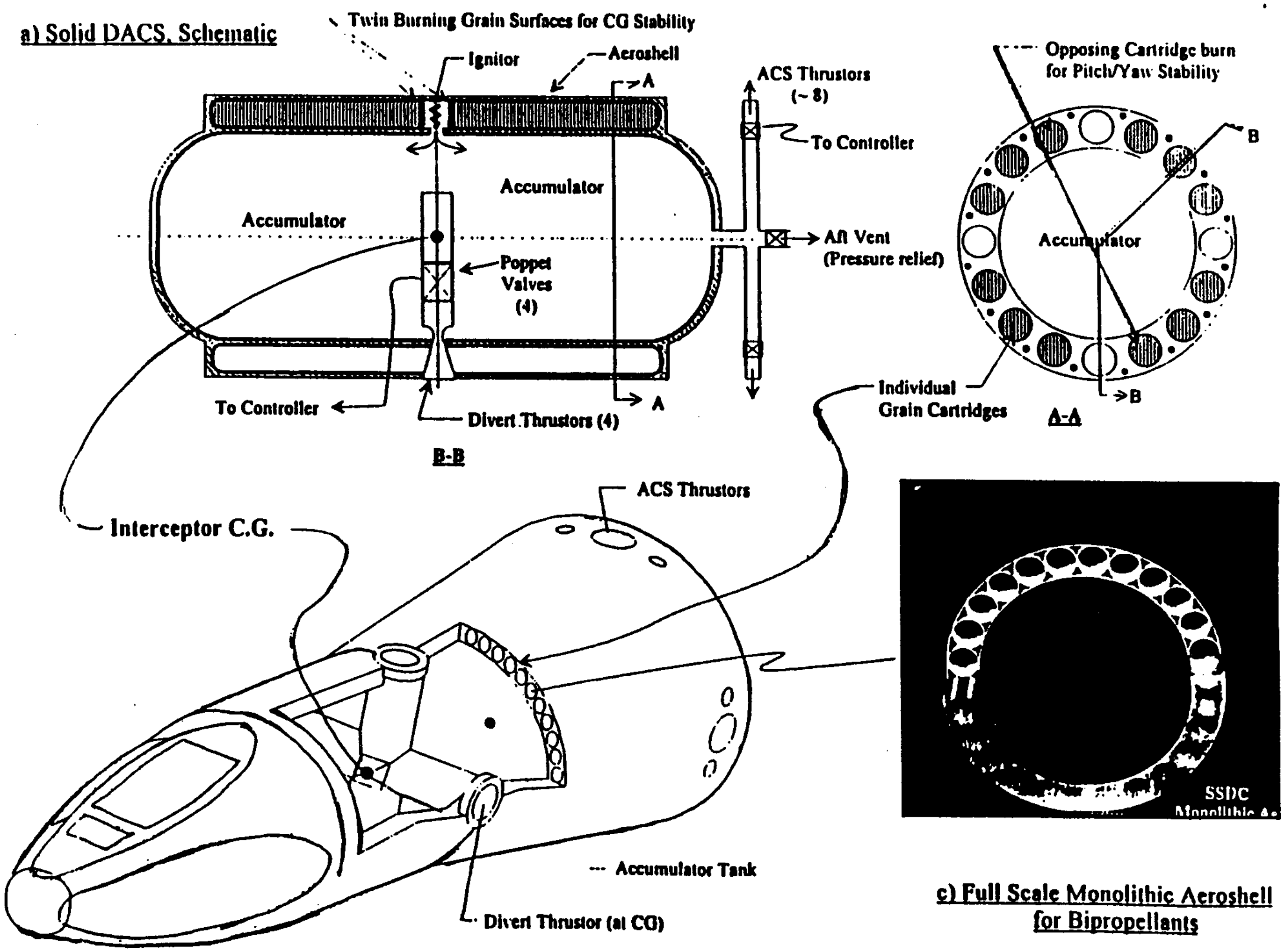
Approaches for Composite Electronic Component Packaging Structures



	METAL SHEET SPUTTER COATING PLATING SURFACE MESH (APPLY) SECONDARILY)	RANDOM NICKEL-COATED GRAPHITE FIBER MAT (NON-WOVEN) (MOLDED-IN)	NICKEL-COATED GRAPHITE FIBER CLOTH (WOVEN) (MOLDED-IN)	CO-WOVEN METAL FILAMENT (MOLDED-IN)
EMI SHIELDING	GOOD	GOOD	EXCELLENT FOR FLAT SHAPES	MINIMAL
GROUND PLANE	EXCELLENT	MINIMAL	GOOD	GOOD

64055-004

SOLID PROPELLANT DACS
INTEGRAL PROPULSION/STRUCTURE -- CONCEPT



a) Solid DACS, Schematic

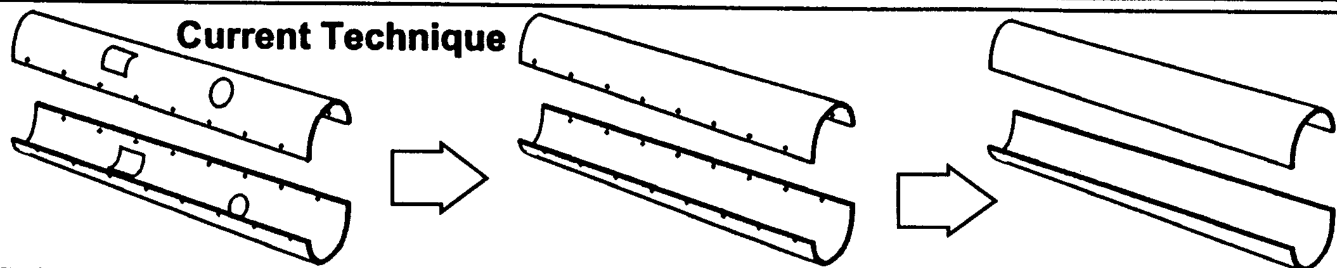
b) Sample Endoatmospheric Interceptor

c) Full Scale Monolithic Aeroshell
for Bipropellants

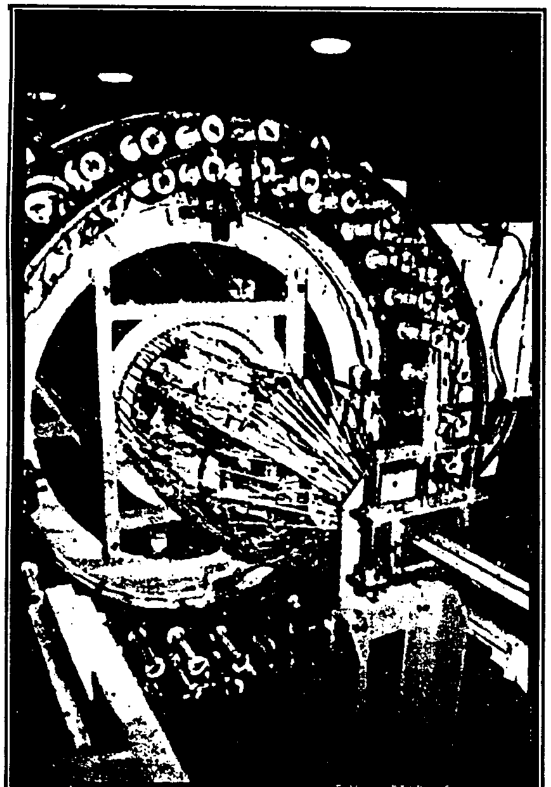
EFEX will Demonstrate New High Temperature Composite Interceptor Structure Technology

4/10/95

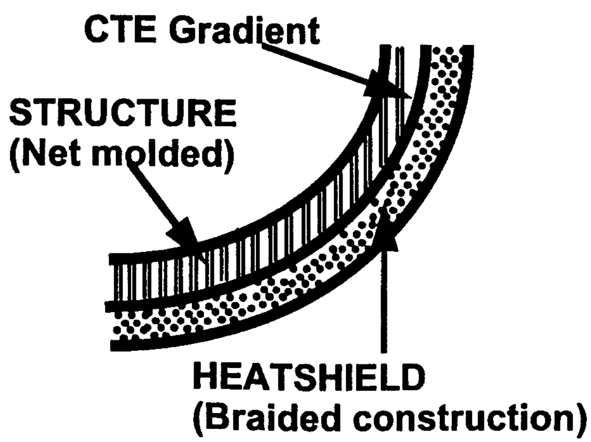
Current Technique



Fabricate Graphite/High Temperature Resin Substructure (Autoclave Cure and Secondary Machine Features)	Fabricate Quartz/Phenolic Heatshield (Tape Layup and Autoclave Cure)	Bond Heatshield to Substructure and Machine Features



New Approach: Low Cost Net Molded Substructure
Low Cost Braided Heatshield
Co-Cure Substructure and Heatshield



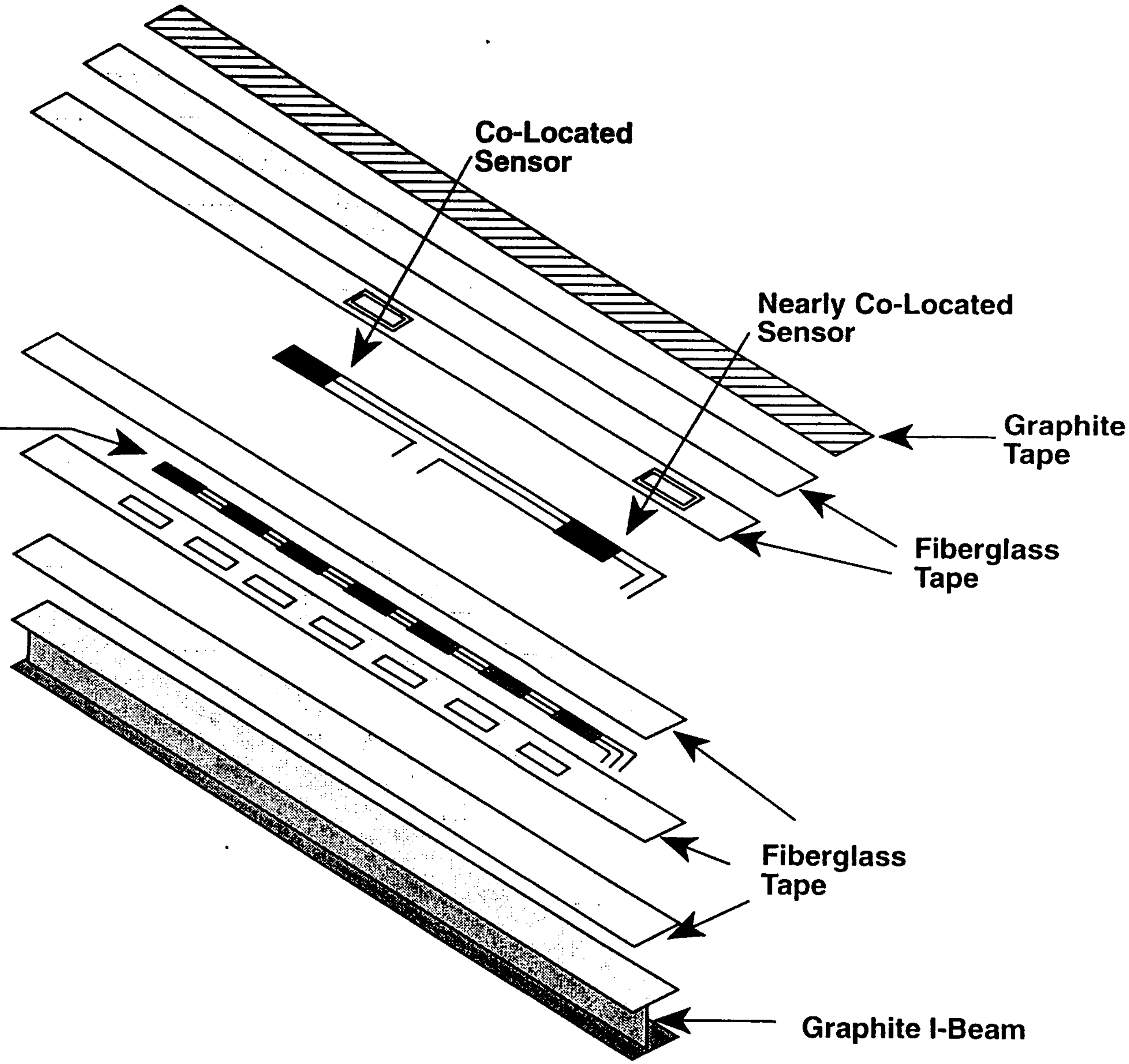
Benefits

- Improved Airframe Structural Thermal Integrity up to 900°F
- Lower Production Cost Status Composite Braid Construction Demonstrated
- Automated Fiber Placement Achieved

km10107

Fabrication of Adaptive Structures

$$L_{ADS} = M_O \cap D_S \cap D_{ACT}$$



Materials

Graphite/Thermoplastics
Graphite/Epoxies
Graphite/Polycyanate
} Struts

Glass/Epoxy
Glass/Thermoplastic
} Actuator Embedding Material

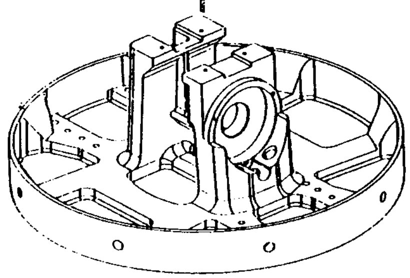
Type O Multi-Functional Structure (M_O) With Integrated Sensors and Acutuators

64055-011

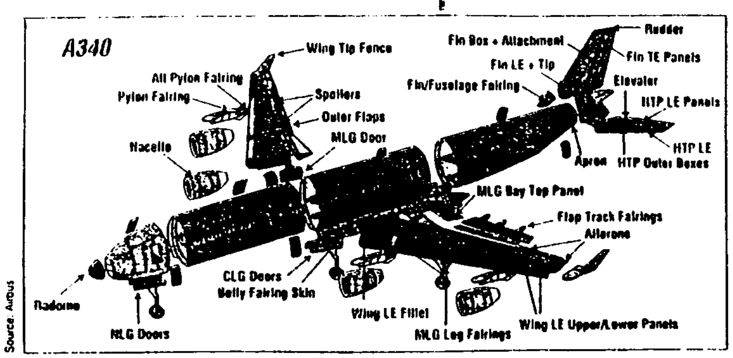
Candidate Closed Mold Fabrication Applications

Markets/Applications

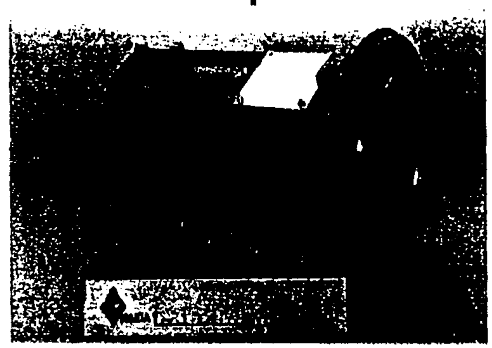
Missiles



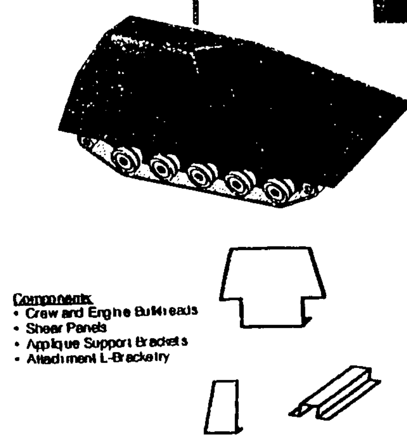
Aircraft Structures



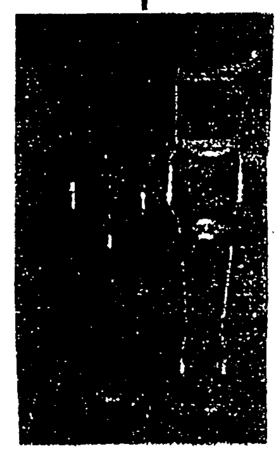
Aerospace Components



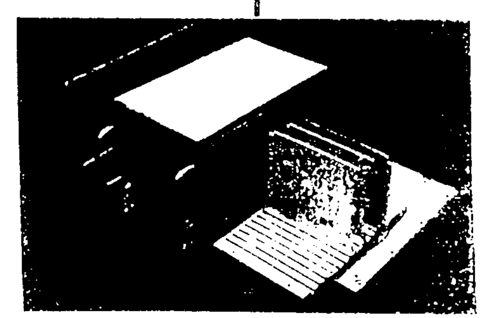
Land Vehicles



Bioengineered Products



Electronic Enclosures



Agile Manufacturing Potential

- **Ability to rapidly modify manufacturing process to meet customized product requirements without sacrificing quality**
- **Desired features:**
  - Rapid tool production
  - Rapid convergence of optimum process
  - Rapid tool change to produce a mix of products
  - Smart process control
  - In situ NDI

Closed mold manufacturing has generic features that allow agile manufacturing of high performance composites.

LESSONS LEARNED FROM AIRCRAFT INDUSTRY EXPERIENCE WITH COMPOSITES STRUCTURES TECHNOLOGY[1]

Organizational Issues

- Structural design, certification, and test requirements as well as materials, processes, manufacturing, tooling, quality control, product support, and cost issues must be understood and addressed from the start
- Costs must be competitive with counterpart metal structures
- A "Concurrent Engineering" approach is favored
    - Should include generalists with multi-disciplinary experience
    - Leads to early problem resolution and reduces costs associated with rework, modifications and changes
    - Enables designers to become familiar with manufacturing and QC technologies, capabilities and problems, and vice versa

---

1 NASA Langley Report #4620

Lessons Learned - Organizational Issues

- There is no substitute for composite experience

    - Composite technology is transferred by people working together, not by reports, presentations and lectures

    - Successful training of key personnel can be accomplished using outside tutorials and training courses as well as in-house programs

- Fewer problems encountered and more rapid problem resolution at companies with co-located engineering and production capabilities

- Experience in R&D programs does not readily transfer to production unless R&D personnel actively participate in production development

Lessons Learned - Structural Design, Analysis, and Test

- Successful programs use a building block approach for development
  - Design, fabrication, and test of structural components taken in steps for early problem identification with the smallest investment in tooling and test complexity
  - Requires realistic schedules to allow systematic development
- Finite element analysis capability adequate for design
  - All members of a particular team should use the same tools
- Number of mechanical joints should be minimized
  - Reduced part count reduces assembly costs
  - However, overly complex tooling negates savings
- Structural designs and associated tooling must be adaptable to accomodate later design changes
- Standardization of techniques for inducing impact damage and assessing its effects is needed
- Designing for producibility is generally more cost effective than optimization for weight savings

Lessons Learned - Materials and Processing

- Conducting materials development in conjunction with a product development program creates undue risks

- Minimizing scrap is essential due to the high material costs

- Designers and process engineers must be readily available during early phases of production
    - Correct production problems
    - Validate changes to roduction processes

- Handbooks that pictorially describe manufacturing processes are easier to interpret than engineering drawings
    - Fewer lay-up and processing errors

- Co-curing/co-bonding preferred over secondary bonding
    - Secondary bonding requires a precision interface fit

Lessons Learned - Manufacturing and Tooling

- Designing for producibility is essential
  - Assembly/fabrication costs determine the design/manufacturing process
  - Automation not cost-effective for low production rates
- Dimensional tolerances are more critical in composites than metals
  - Avoid shimming during assembly, out-of-plane loads
  - Selection of tool material is dependent on part size and configuration, production rate and quantity, and company experience
  - Quality tools are essential for the low-cost production of quality parts

Lessons Learned - Quality Control

- QC costs for composites are much higher than for metal structures

    - Automated processes can reduce costs

    - Focus inspection and control on aspects of the process that have a direct bearing on part quality and performance

    - Determine the effects of defects on part performance

Lessons Learned - Supportability

- Supportability has not been adequately addressed during design
  - Most damage occurs during assembly and routine maintenance
  - Repair costs are much higher than for metal structures
  - Improved records are needed
  - Special long-life/low temperature cure repair materials are required
  - Moisture ingestion and aluminum, core corrosion are a recurring supportability problem for honeycomb structures

Why are we here?

Workshop on Closed Mold Manufacturing
15-15 May 1995

Dr. Janet Sater
Institute for Defense Analyses

General Workshop Objectives

- Increase communication among end users, material suppliers, and composite parts manufacturers

- Identify technical issues and limitations associated with the application and closed mold manufacturing of high performance polymer composites for missile structures

Topics - Missile Producers

- Information required for the application of advanced composites to real missile systems (primary and secondary structure) including data on processes, properties, qualification tests

- Expectations for operational functions of composite missile structures

  i.e., ability to handle loads, thermal management, electro-magnetic interference, charging, lightning strike protection

- Other issues that need to be address for application and production

  i.e., program schedules, cost sensitivities, production lot sizes, expected composite structure lifetimes, assembly/disassembly cycles, reparability, disposal

Topics - Material Suppliers - Preforms

- Preform technology

  i.e., fiber options, fiber architectures

- Manufacturing limitations

  i.e., preform size, achievable fiber volume fractions, minimum fiber bend radii, fiber sizing, equipment availability, methods to assure quality

Topics - Material Suppliers - Resins

- Resins for closed mold manufacturing
  i.e., resin options, processing limitations

- Methods to assure quality and to address problems with existing resins

- Drivers for developing new resins

- Other issues such as government regulations or other restrictions that may affect supply

Topics - Material Suppliers - Prepregs

- Prepreg technology

  i.e., fiber and resin options, manufacturing limitations

- Methods to assure quality

Topics - Composite Part Fabricators

- Difficulties with closed-mold manufacturing of high performance polymer composite structures
  - i.e., material uniformity, processing-related issues
- Results or data from any additional testing
  - i.e., materials used (fiber architectures, matrix), density (porosity), other physical and mechanical properties
- Estimated current and projected costs with respect to production lot size
- Description of desirable new materials (resins, preforms)
- Other manufacturing and joining issues
  - i.e., lessons learned that will increase confidence of missile producers in these composite structures

APPENDIX C

MISSILE SYSTEM PRODUCER PERSPECTIVES

LOCKHEED MARTIN
MISSILES & SPACE

MISSILE
SYSTEMS
DIVISION

CLOSED-MOLDED HIGH PERFORMANCE COMPOSITE STRUCTURES

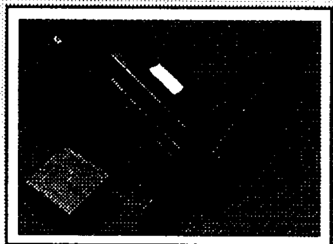
May 15-16
Alexandria , VA

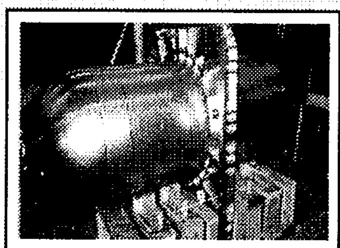
Tom Anderson
408-743-7140

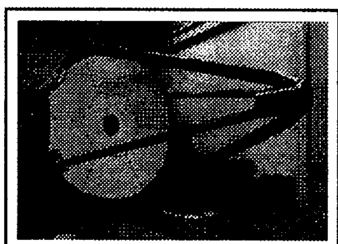

MSD
Lockheed Martin Missiles & Space
Trident II
ERIS
THAAD
PROVEN PROJECT LEADERSHIP
IN DIVERSE PROGRAMS
LOCKHEED MARTIN

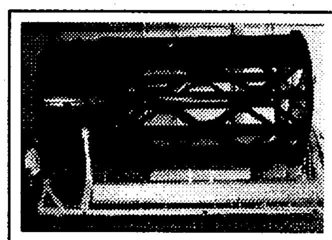
Structural Design & Materials Engineering

ADVANCED MATERIALS & STRUCTURES





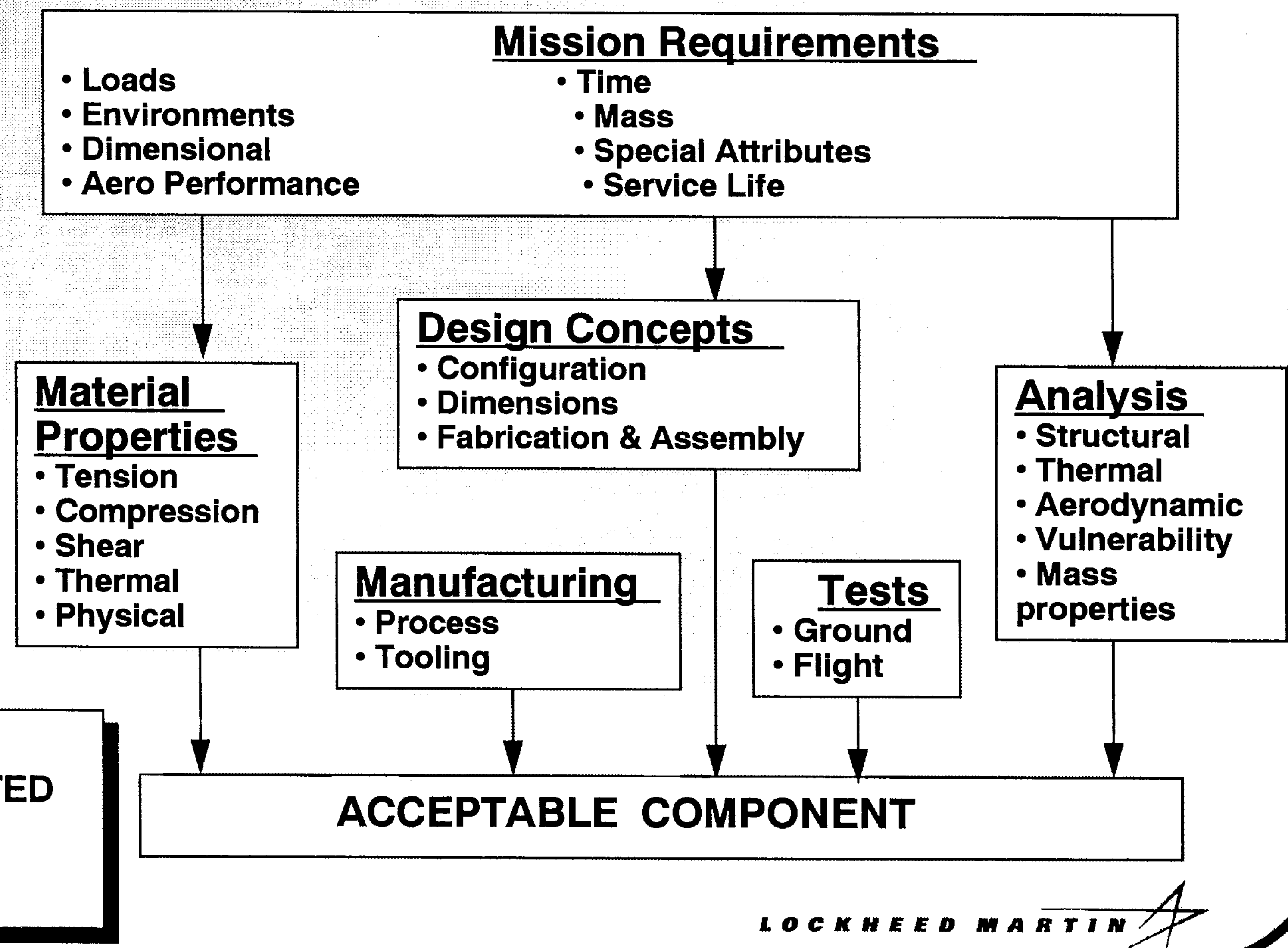




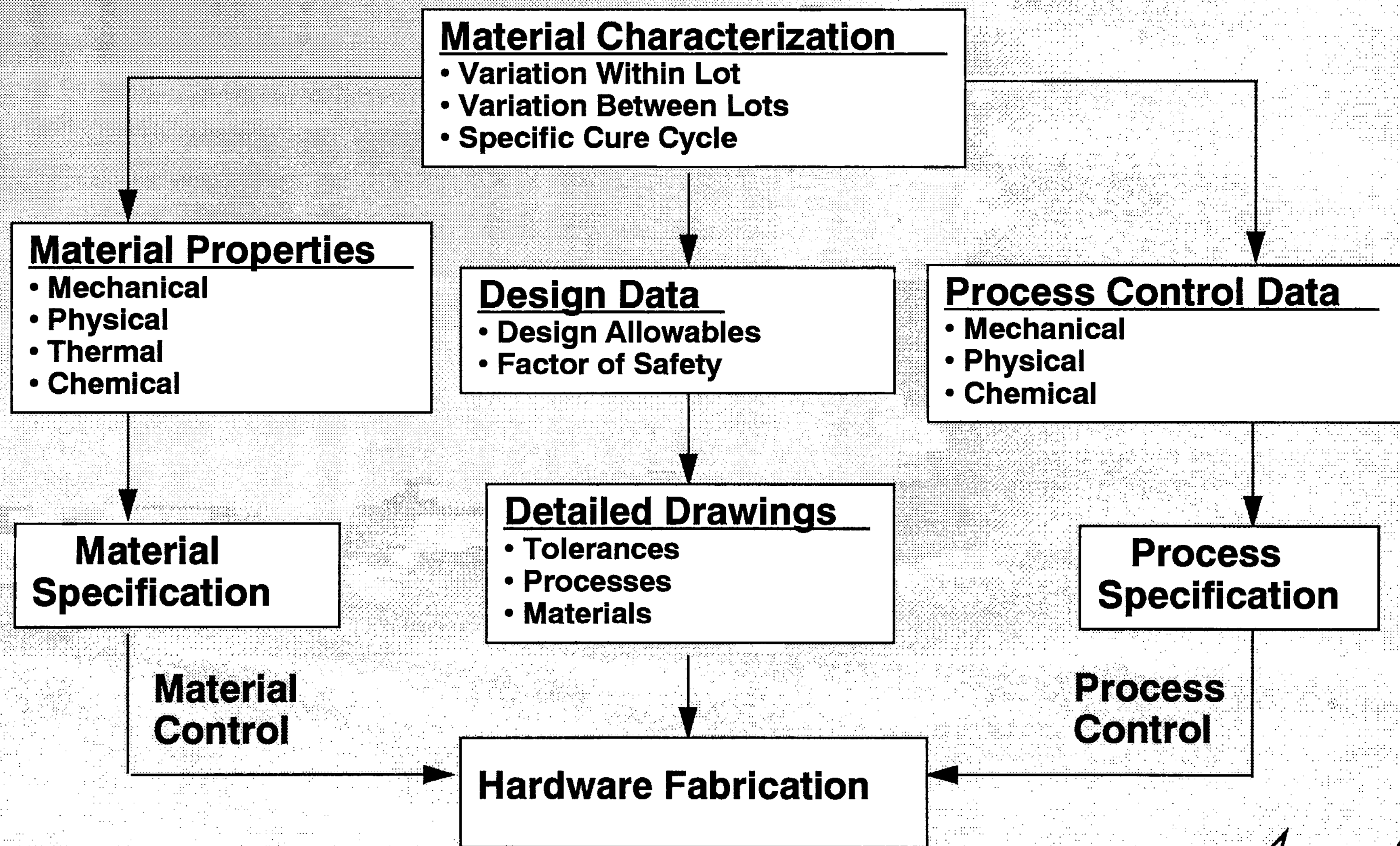
- **Demonstrated Capability to Design, Analyse, Fabricate and Test**
- **Unique Critical Skills**
  - Nosetips, Leading Edges & Heatshields
  - Shrouds & Missile Bodies
  - Pressure Vessels & Bulkheads
  - High Strength / Stiffness
  - Signature Reduction
  - Thermal Management
- **Established Development, Characterization and Control Capabilities**
  - Material & Process Engineering
  - Engineering Development Laboratory

LOCKHEED MARTIN

Team Product Design Process



Material & Process Development



LOCKHEED MARTIN

MSD

Subcontractor Requirements

ALL Subcontractors

- Process Documentation
- Process Proofing
- Notification of Process Changes
- Qualified Sub-Tier Suppliers
- Lot / Component Traceability
  - Variation Within Lot
  - Variation Between Lots

MATERIAL Subcontractors

- Fiber Properties
- Resin Properties

COMPONENT Subcontractors

- Non-Destructive Inspection
- Tag-end Testing
- "Traveler" Specimen Testing
- Component Level Testing

PROCESS DISCIPLINE MANDATORY

LOCKHEED MARTIN

Composite Structure Production Experience

PRESS MOLDED

Trident I - C4 Missile

• 3rd Stage Rings	2
• Eject Cylinder Forward Ring	1
• Nose Fairing Guides	8
• "Pizza Pans"	8
• Misc. Brackets / Stiffeners	61
	80

80 x 588 shipsets = 47,040 parts

Trident II - D5 Missile

• "Pizza Pans"	8
	8

8 x 388 shipsets = 3,104 parts

82,408 HAND LAYUP ADVANCED COMPOSITE STRUCTURAL COMPONENTS

AUTOCLAVE MOLDED

Trident I - C4 Missile

• Primary Structure Shell	1
• T.S. Motor Support Cone	3
• T.S. Motor Ring	1
• Eject Cylinder	1
• Eject Cylinder Mid-Ring	1
• T.S. Motor Equip. Module	2
• Bond Cure Cycle	1
	10

10 x 588 shipsets = 5880 parts

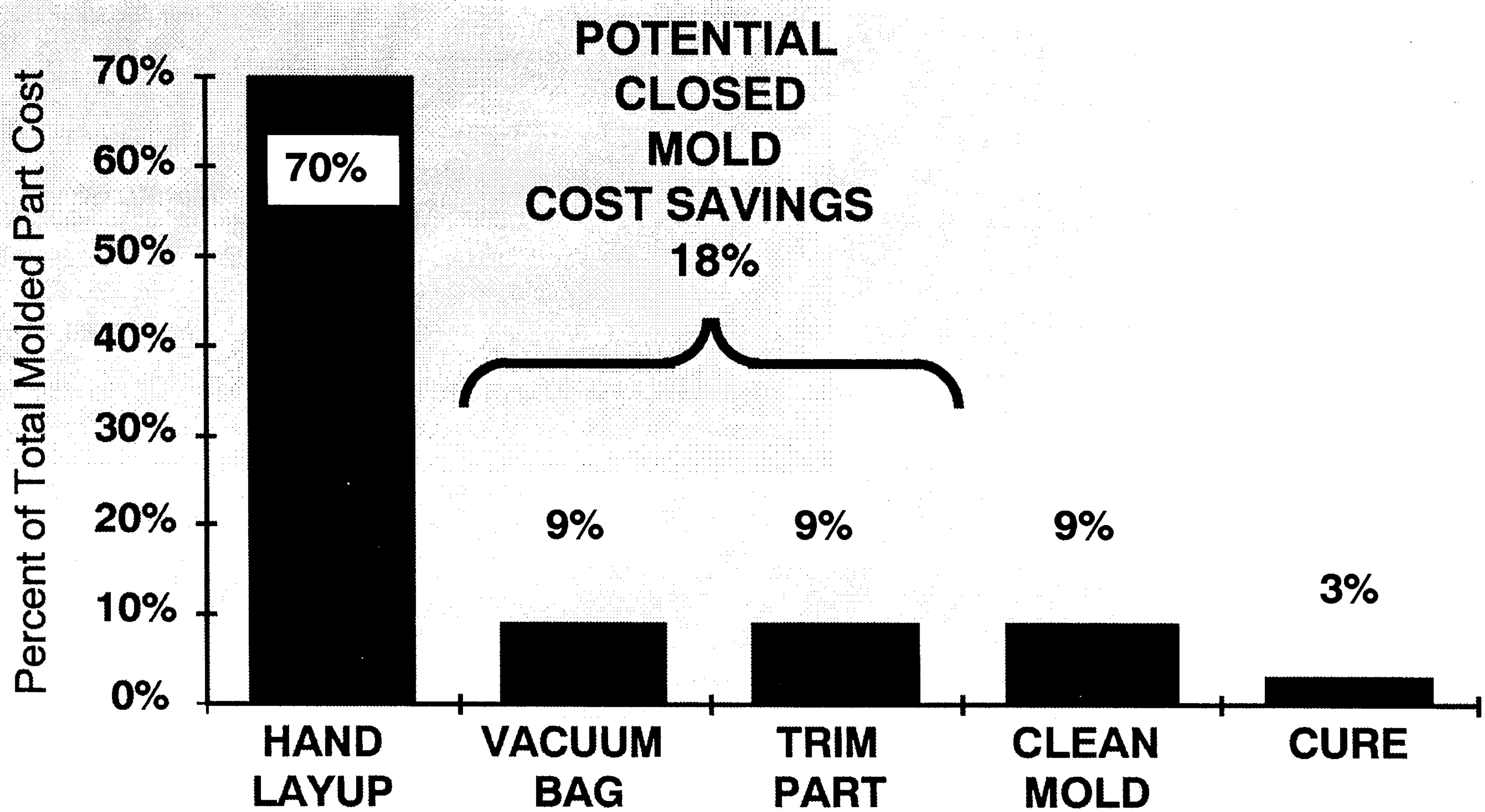
Trident II - D5 Missile

• Primary Structure Shell	1
• Main Beam	12
• Stiffeners & Ribs	24
• Aft Shear Panel	1
• Fwd. Stiffener Ring	1
• Misc.	29
	68

68 x 388 shipsets = 26,384 parts

LOCKHEED MARTIN

Closed Molding Savings



LOCKHEED EFFORTS APPLIED TO LAYUP COST SAVINGS

LOCKHEED MARTIN

MSD

Net Closed Molding Implementation

CONCERNS

- Program Risk Mitigation
  - Untried manufacturing technologies raise concerns
- Longer Learning Curve for New Fabrication Technology

OBSTACLES

- Initial Limited Program Quantities
  - Drive Low Non-Recurring Cost Processes
- Limited Development Spans
  - Require Mature Materials & Processes
- Customer Configuration Management Requirements
  - Promote No Change Policy

LOCKHEED MARTIN

MSD

Recommendations

TECHNOLOGY ORGANIZATIONS

- Fund Technology Programs in time for Program Consideration
- Involve Primes & Suppliers in the Technology Development
- Standardize Data Development Methods
- Make the Database Available to all users

PROGRAM / PROJECT OFFICES

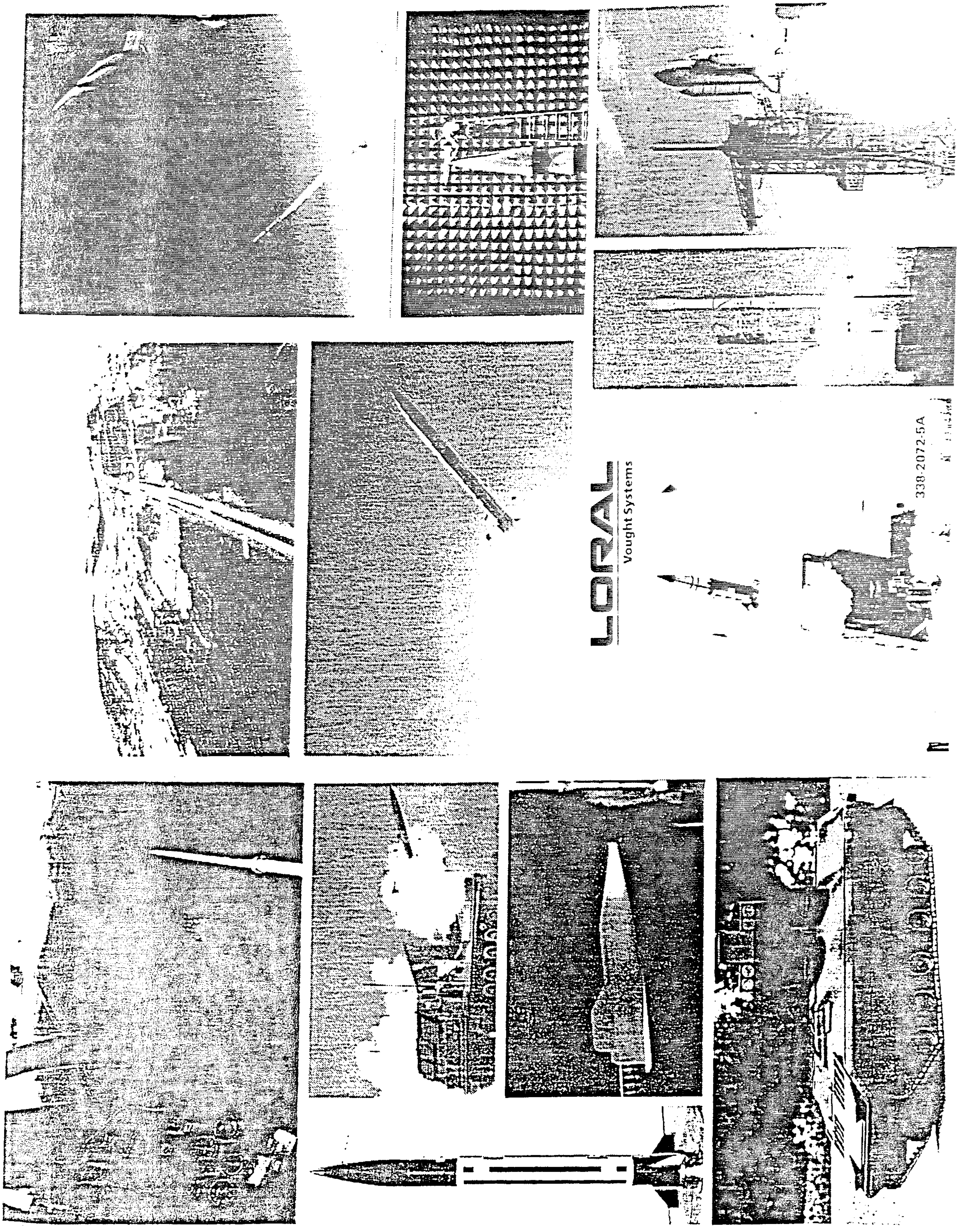
- Make Producibility a Distinct Contract Item
- Allocate Producibility "Block-Upgrades" in Each Contract Phase

LOCKHEED MARTIN

COMPOSITE STRUCTURES
--- MISSILE APPLICATIONS ---

TZU-LI HO

LORAL VOUGHT SYSTEMS
DALLAS, TEXAS


LORAL
Vought Systems
338-2072-5A

LV COMPOSITE STRUCTURES

- Missiles
  - Shell Body
  - Control Surfaces
  - Nose/Radome
  - Rocket Motor
- Launch Pod Container
- Space Shuttle Carbon-Carbon Parts

COMPOSITE STRUCTURAL DESIGNS

- High Temperature Compatibility
    - CTE Compatibility
    - Oxidational Resistance
    - Chemical Compatibility
    - Duration
    - Temperature Levels

- Manufacturer's Capability
    - Processability
    - Tooling Design

- Structural Capability
    - Strength And Stiffness
    - Durability
    - Non-linear Response

- Test And Evaluation

LORAL
Vought Systems

OTHER STRUCTURAL ASPECTS

- Composite structures
  - Fiber-Reinforced Composites
  - Carbon-Carbon Composite
  - Special Anisotropic Structure Application
- Design Criteria And Requirements
  - Environments
  - Operational Requirements
- Analysis Tools
  - Softwares
  - Allowables
  - Literature
- Test And Evaluations

NATURAL ENVIRONMENT APPLICATIONS CHART

ENVIRONMENTAL CONDITIONS	CANISTER		MISSILE		MMS	FSC
	TRANSPORT	LAUNCH STATION	IN CANISTER	IN FLIGHT	LAUNCH STATION	ENGAGEMENT CTRL STA
TEMPERATURE	X	X	X	X	X	X
TEMPERATURE SHOCK	X	X	X	X	X	X
ALTITUDE	X	X	X	X	X	X
RAPID DECOMPRESSION	X	X	X	X	X	
HUMIDITY	X	X	X	X	X	X
SALT-SEA	X	X			X	
WIND	X	X		X	X	
SAND AND DUST	X	X		X	X	
RAIN	X	X		X	X	
HAIL	X	X			X	
ICE, FROST & SNOW	X	X			X	
ICE ON TUBE COVER				X		
FUNGI, BACTERIA,...	X	X	X		X	
FORDING/IMMERSION	X	X	X		X	

BLANK - NOT APPLICABLE
X - ALLOCATED ENVIRONMENT

03/08/94.SKOCZLASSRR.JMR.3

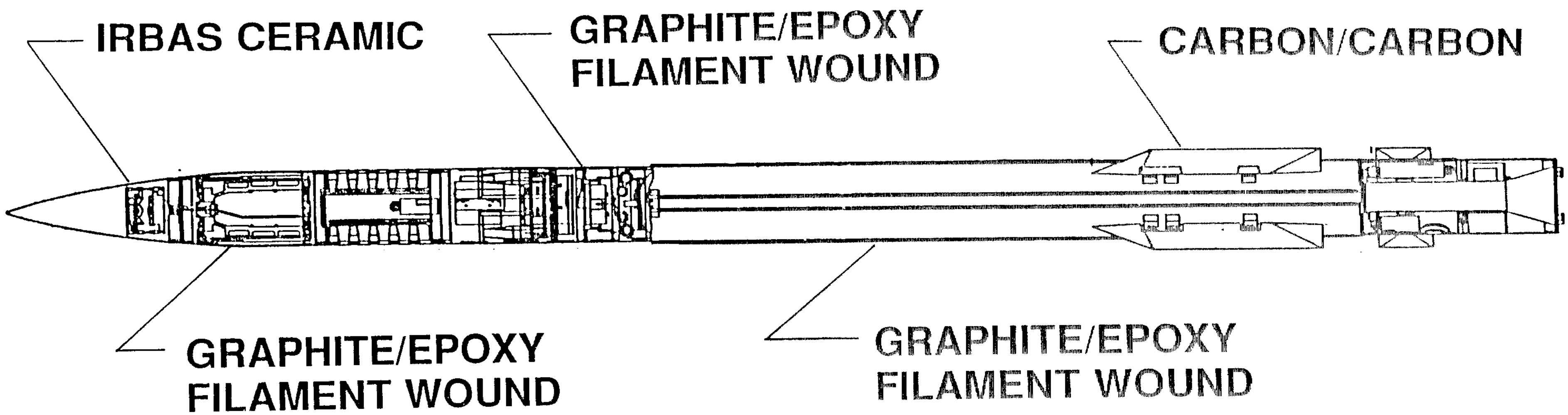
INDUCED ENVIRONMENT APPLICATIONS CHART

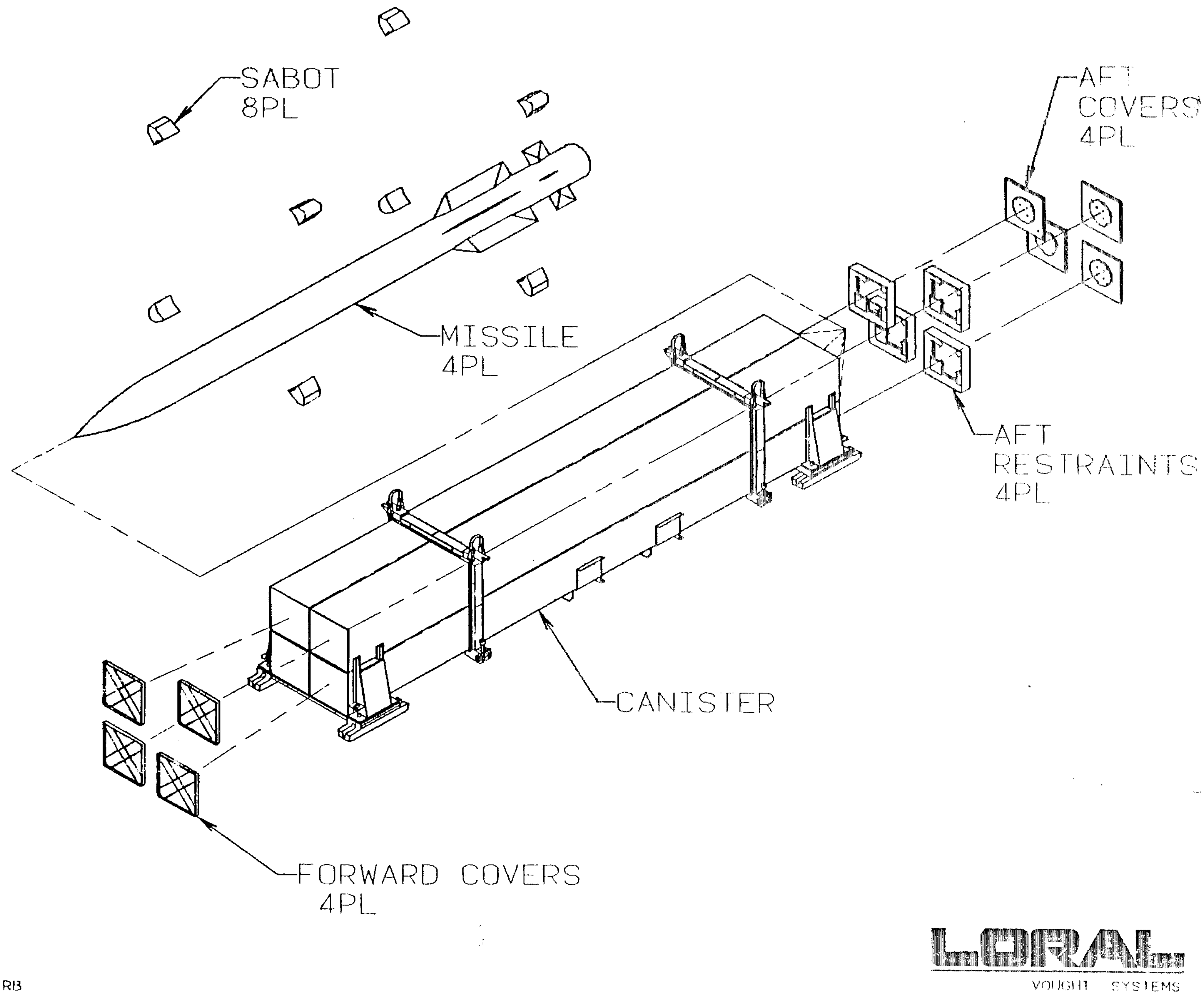
ENVIRONMENTAL CONDITIONS	CANISTER		MISSILE		MMS	FSC COMPONENTS
	TRANSPORT	LAUNCH STATION	IN CANISTER	IN FLIGHT	LAUNCH STATION	ENGAGEMNT CTRL STA
SHOCK						
RAIL IMPACT	X	X	X		X	X
TRANSIT DROP	X		X		SHIPPING CONTAINER	SHIPPING CONTAINER
LAUNCH		X	X	X	X	
FLIGHT (ACM & COVER DEPLOY)				X		
ACOUSTICS		X	X	X	X	
BENCH HANDLING DROP			COMPONENTS		COMPONENTS	X
VIBRATION						
COMMON CARRIER	X	X	X		X	X
TACTICAL TRANSPORT, BRAKING, ENDURANCE	X	X	X		X	X
MISSILE LAUNCH		X	X	X	X	
MISSILE FLIGHT				X		
ACCELERATION						
TRANSPORT	X	X	X		X	X
FLIGHT				X		
NBC DECONTAMINATION SPRAY	X	X			X	

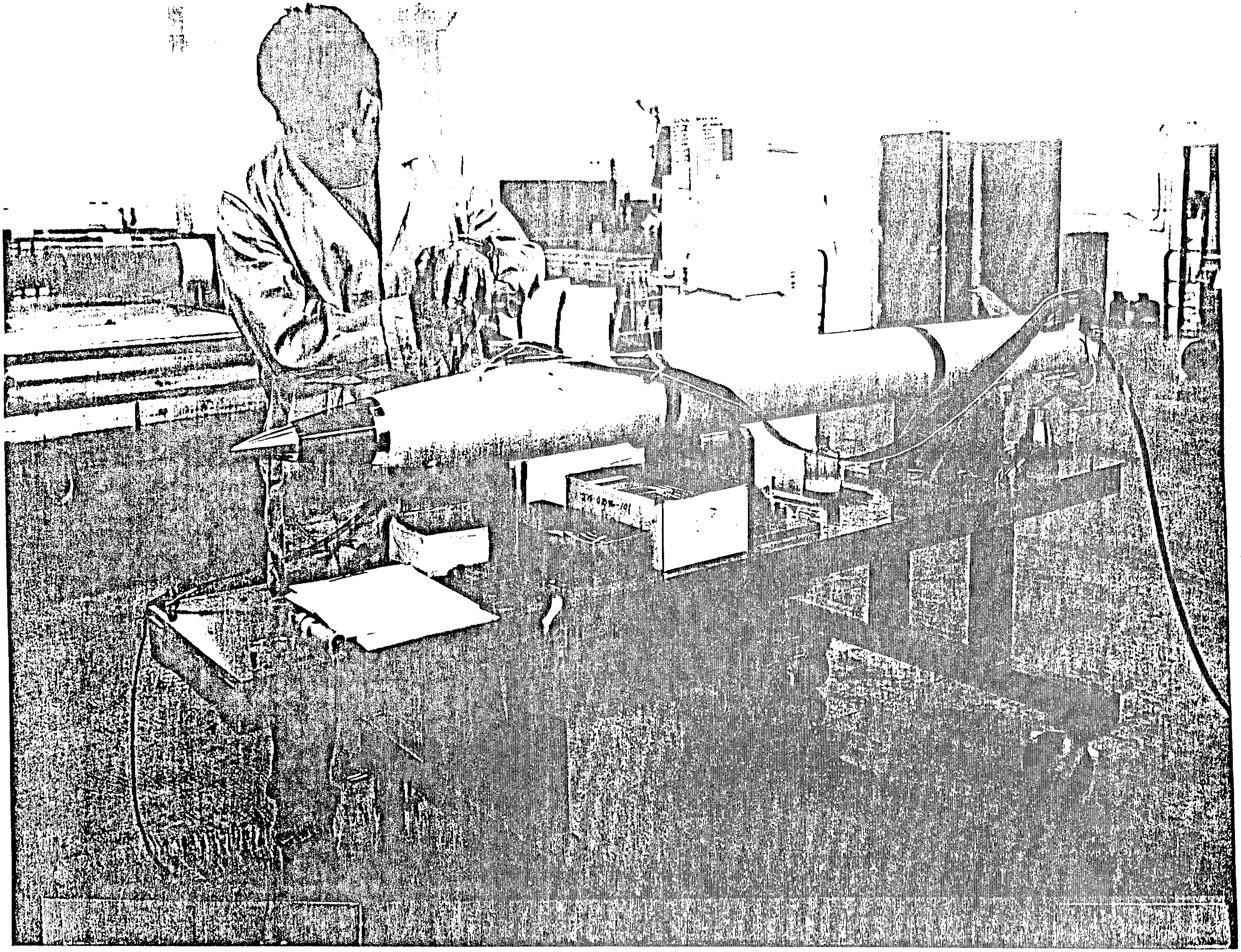
BLANK - NOT APPLICABLE
X - ALLOCATED ENVIRONMENT

PAC-3 MISSILE STRUCTURE

ADVANCED MATERIAL SYSTEMS

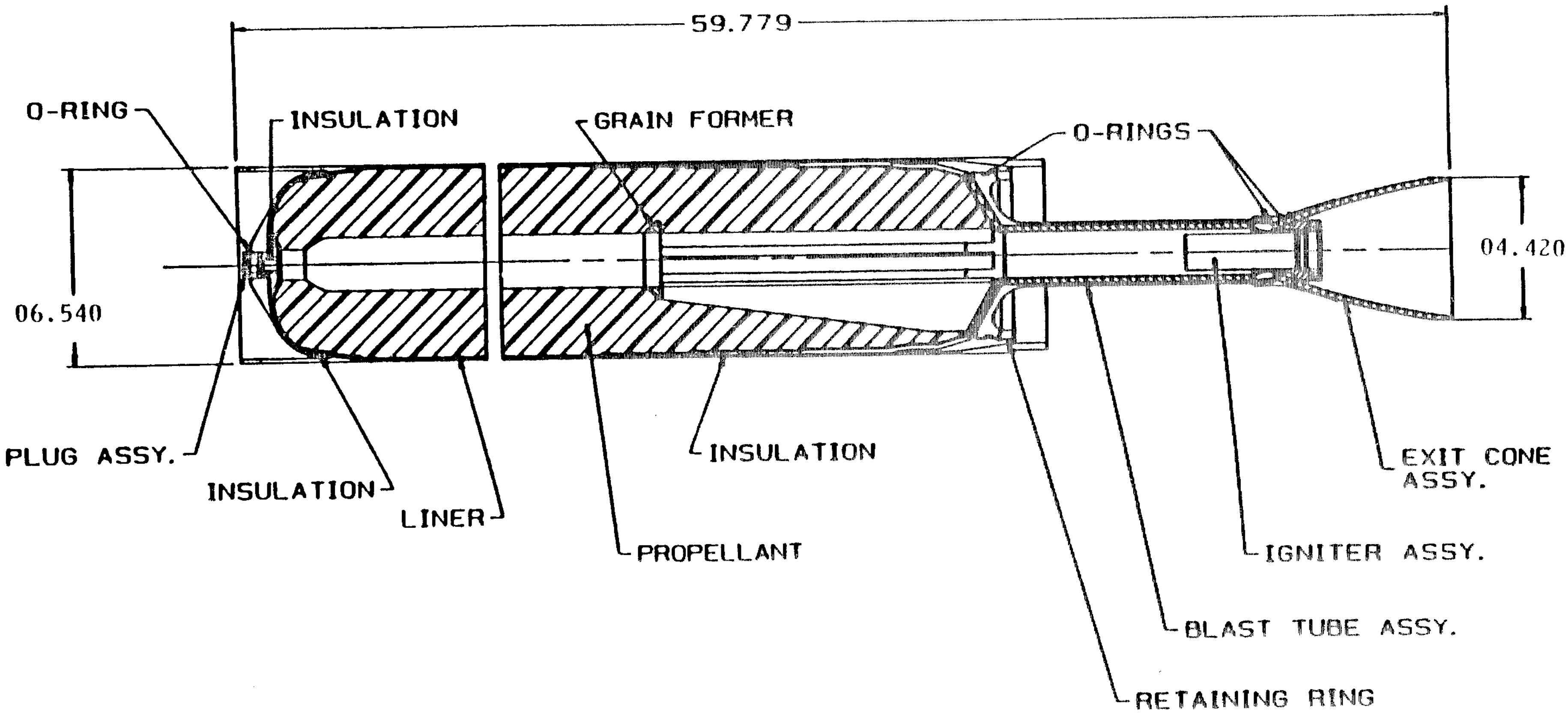



SABOT
8PL
MISSILE
4PL
AFT
COVERS
4PL
AFT
RESTRAINTS
4PL
CANISTER
FORWARD COVERS
4PL
LORAL
VOUGHT SYSTEMS
10-13-92 RB



MISSILE ASSEMBLY (275-01001)

VT-1 MOTOR

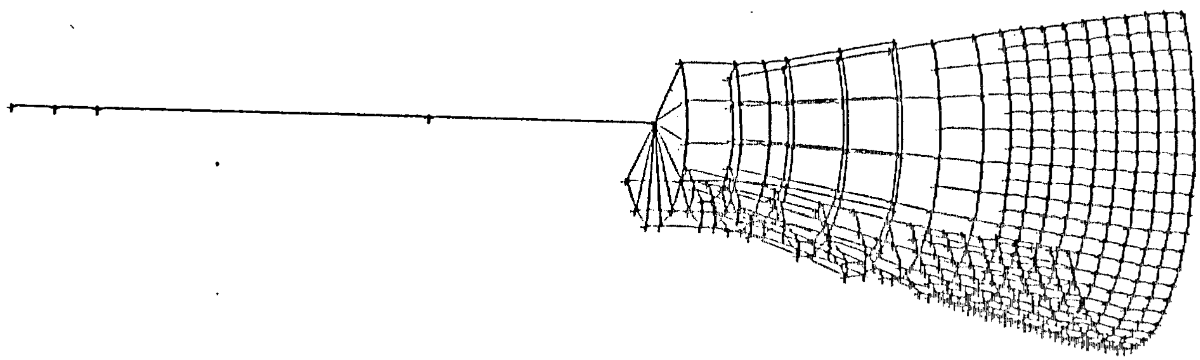


59.779
O-RING
INSULATION
GRAIN FORMER
O-RINGS
06.540
04.420
PLUG ASSY.
INSULATION
LINER
PROPELLANT
INSULATION
EXIT CONE
ASSY.
IGNITER ASSY.
BLAST TUBE ASSY.
RETAINING RING

5

LORAL
Vought Systems

STRESS ANALYSIS AND FINITE ELEMENT MODELLING



Test Data
- Strain Gage
- Pressure Gage
- T/C Data

Environment
- Hot
- RT
- Cold

Geometry
- Fresh
- Eroded

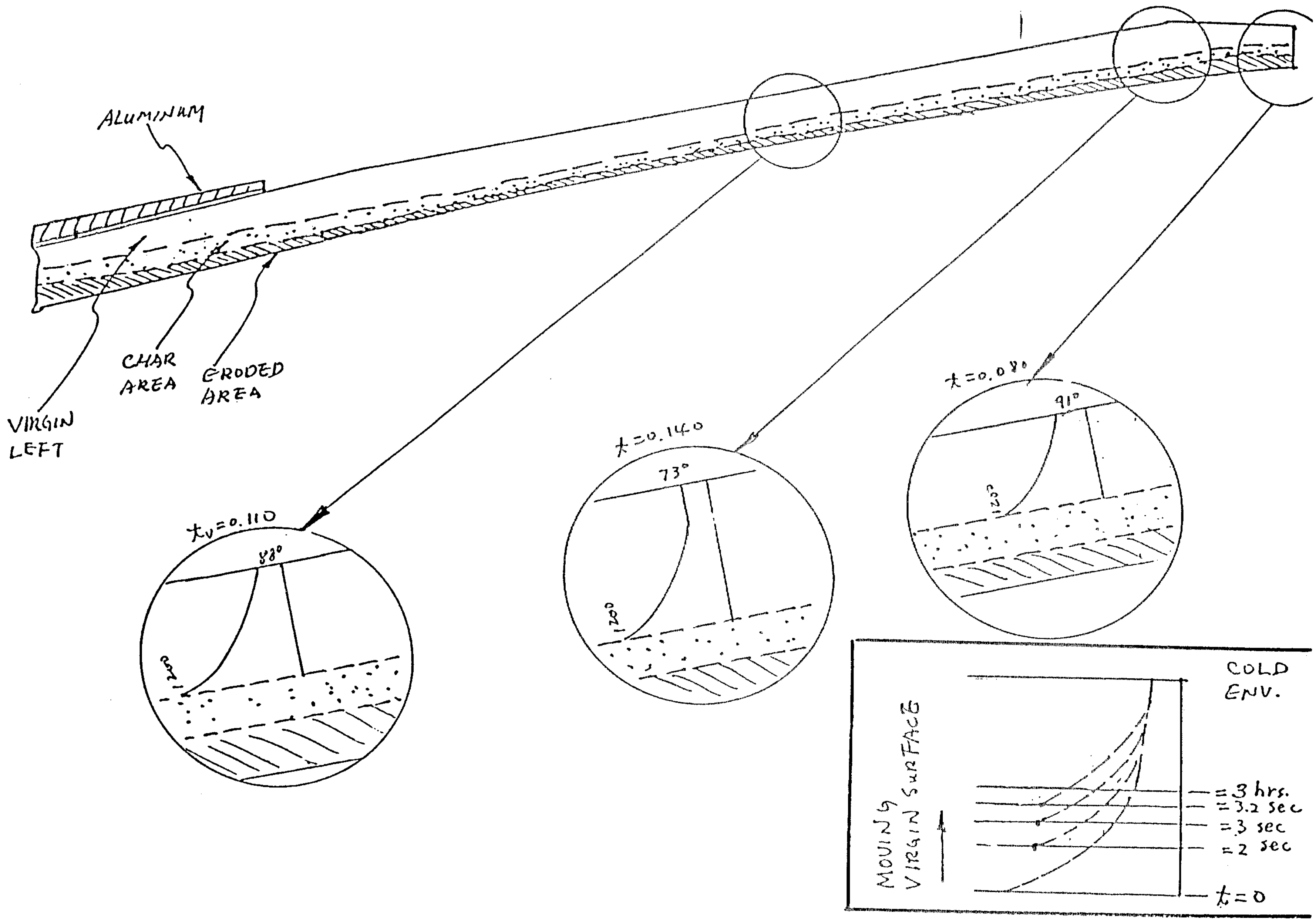
Thermal Prop.
- Heat Conduction
- Temp. Profile

Load
- Shock
- Static Pressure
- Boundary Conditions

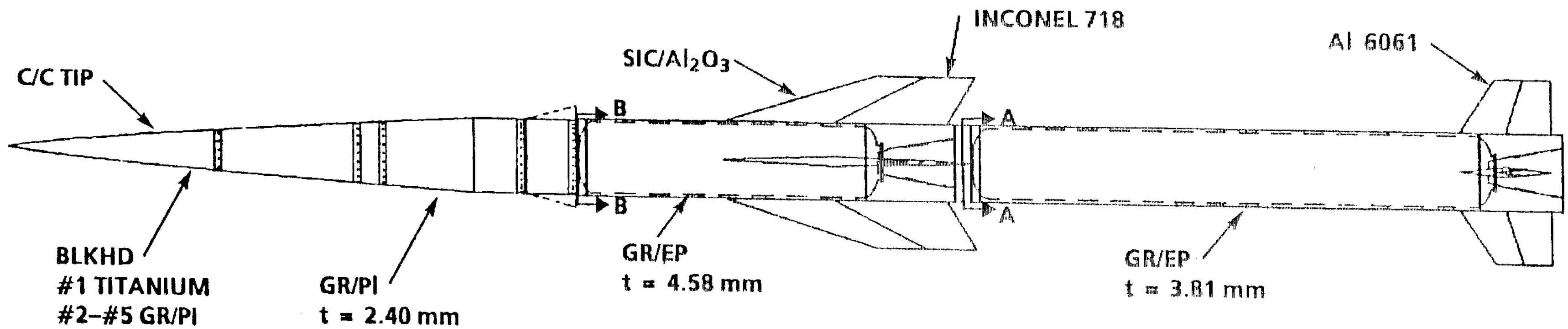
Mechanical Systems

LORAL Vought Systems

MATERIAL PROFILE AND TEMPERATURE DISTRIBUTION



STRUCTURE FOR HIGH PERFORMANCE MISSILE



HIGHER TEMPERATURE COMPOSITE MATERIALS DEVELOPMENT

- INCREASED PERFORMANCE LEADS TO HIGHER OPERATING TEMPERATURES
- EFFICIENCIES INCREASE AS OPERATING TEMPERATURES INCREASE
- HOSTILE OPERATIONAL ENVIRONMENT EXPERIENCED FOR MANY SYSTEMS
- FLIGHT VEHICLES CONSTRAINED IN SIZE AND WEIGHT
- HIGH STRENGTH AND STIFFNESS REQUIRED FOR FLIGHT LOADS

CLOSED MOLD COMPOSITE TECHNOLOGY FOR TACTICAL MISSILE SYSTEMS

Dr. Leslie D. Kramer, P.E.
Manager - Advanced Materials and Structures
Research and Technology Department
Martin Marietta Electronics and Missiles
Orlando, Florida 32819-8907

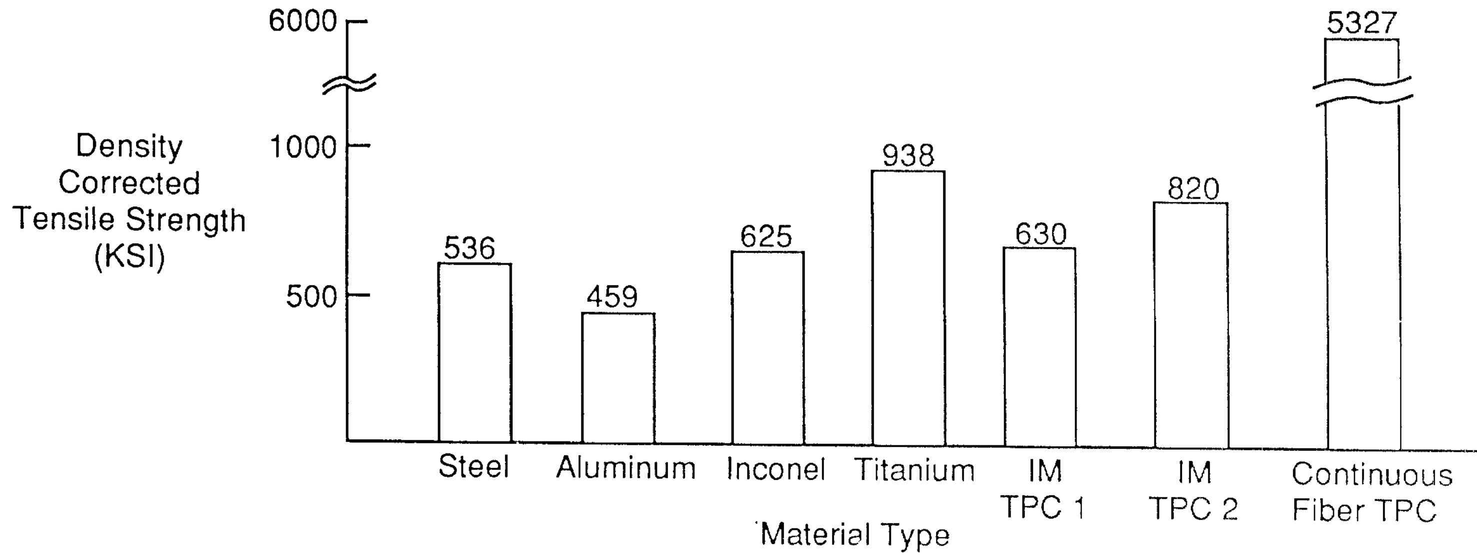
ITEMS FOR DISCUSSION TACTICAL MISSILE APPLICATIONS

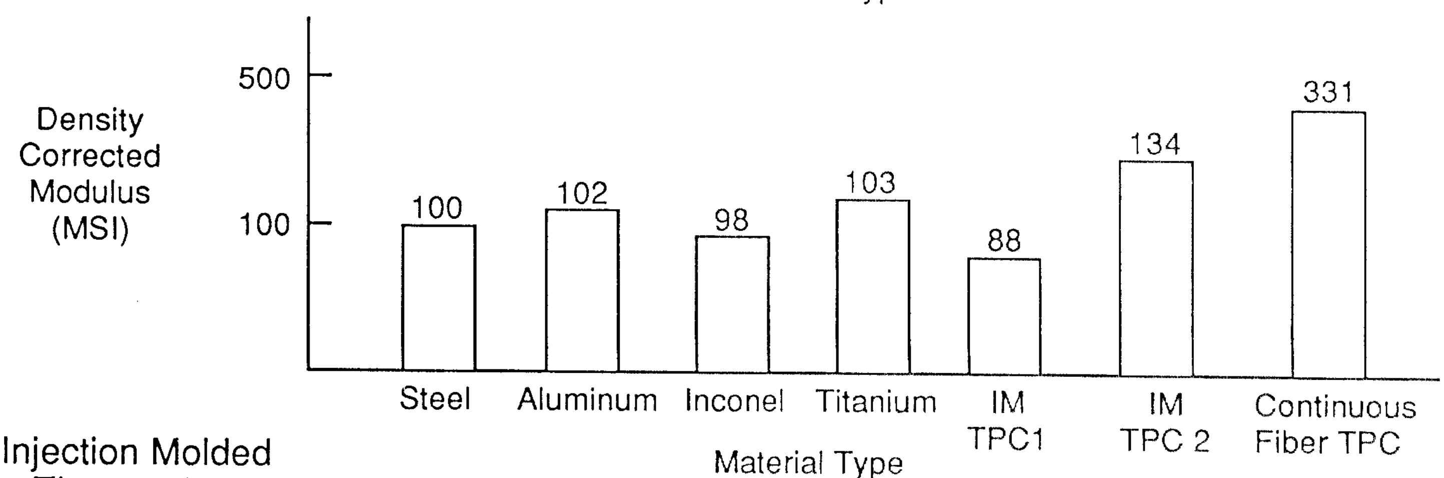
- Design Requirements and Low Cost - Net Shape Drives Application
- Injection Molding of Primary Structures - A Net Shape Technology
- Javelin - An Injection Molding and Matched Metal Molding Success Story
- Longbow Missile and Radar - Closed Mold Methods Reduce Cost
- Other R's - Rapid Prototyping, RTM Simulation, and Recycling

TACTICAL MISSILE NET SHAPE DESIGNS LEAD TO LOW COST COMPONENTS

- Properties and Service Environment
- Component Cost Highly Dependent on Fabrication Method
- Composite Design for Assembly

A Comparison of Common Aerospace Materials



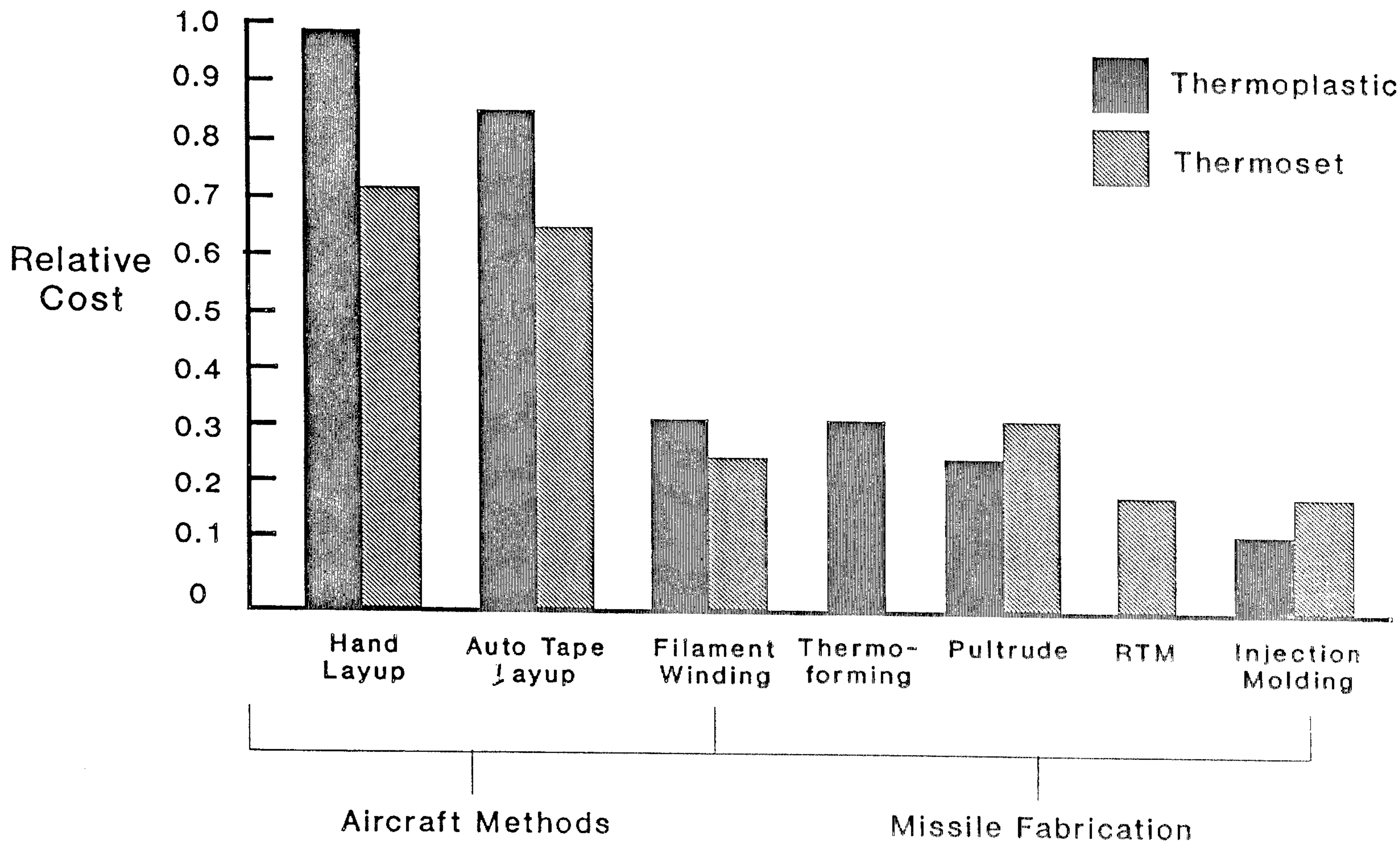


IM = Injection Molded
TPC = Thermoplastic Composite

MARTIN MARIETTA

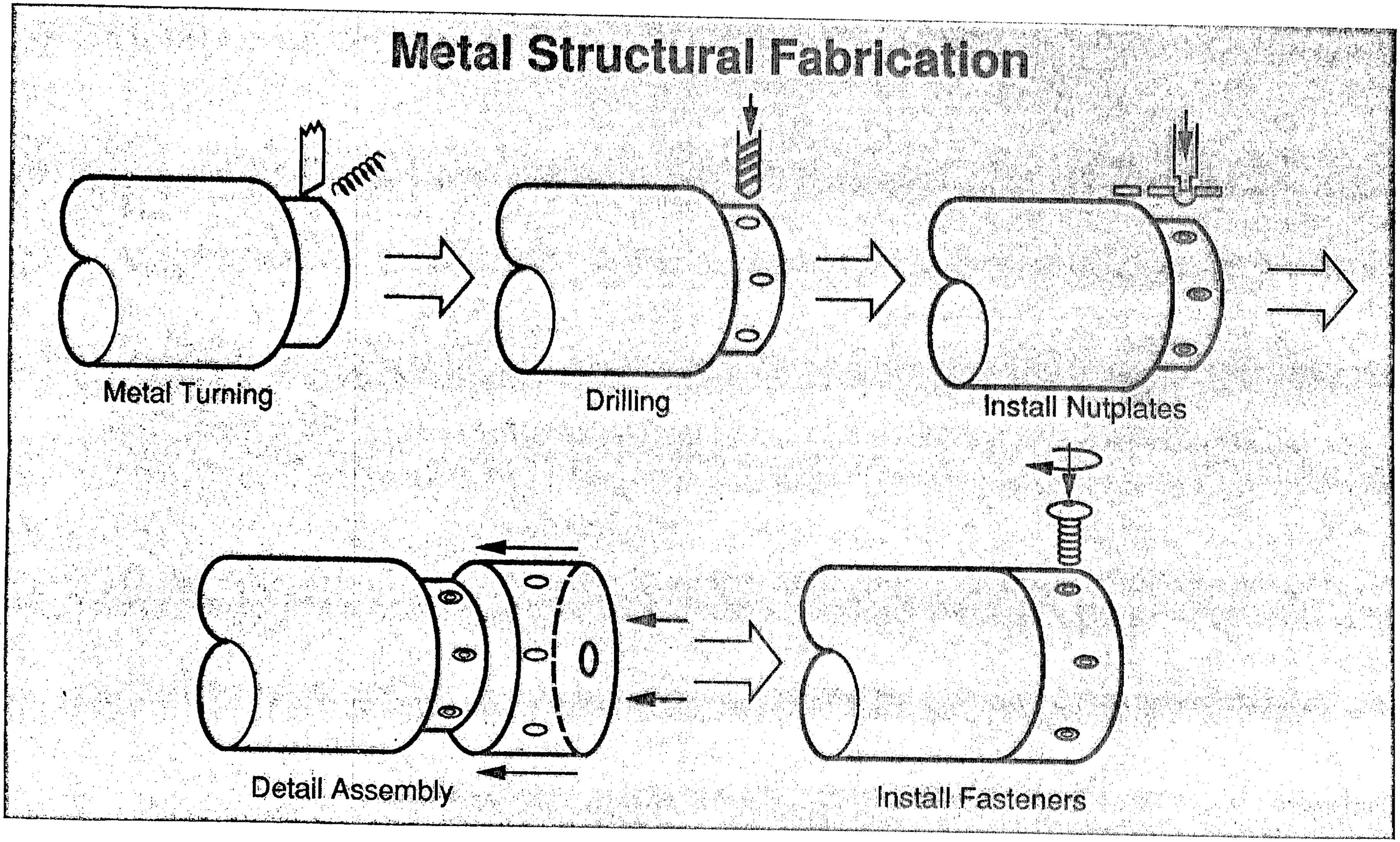
C041-4119.4

Composite Fabrication Method Cost Comparison

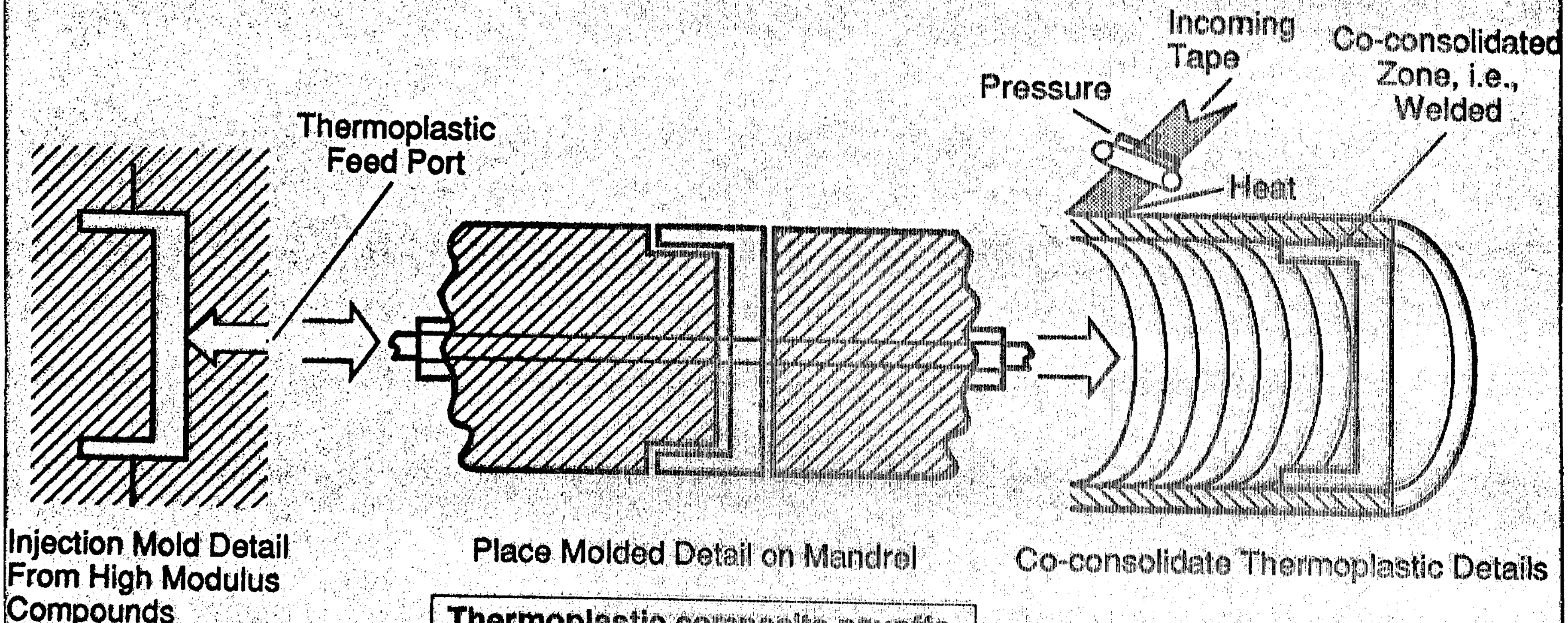


MARTIN MARIETTA

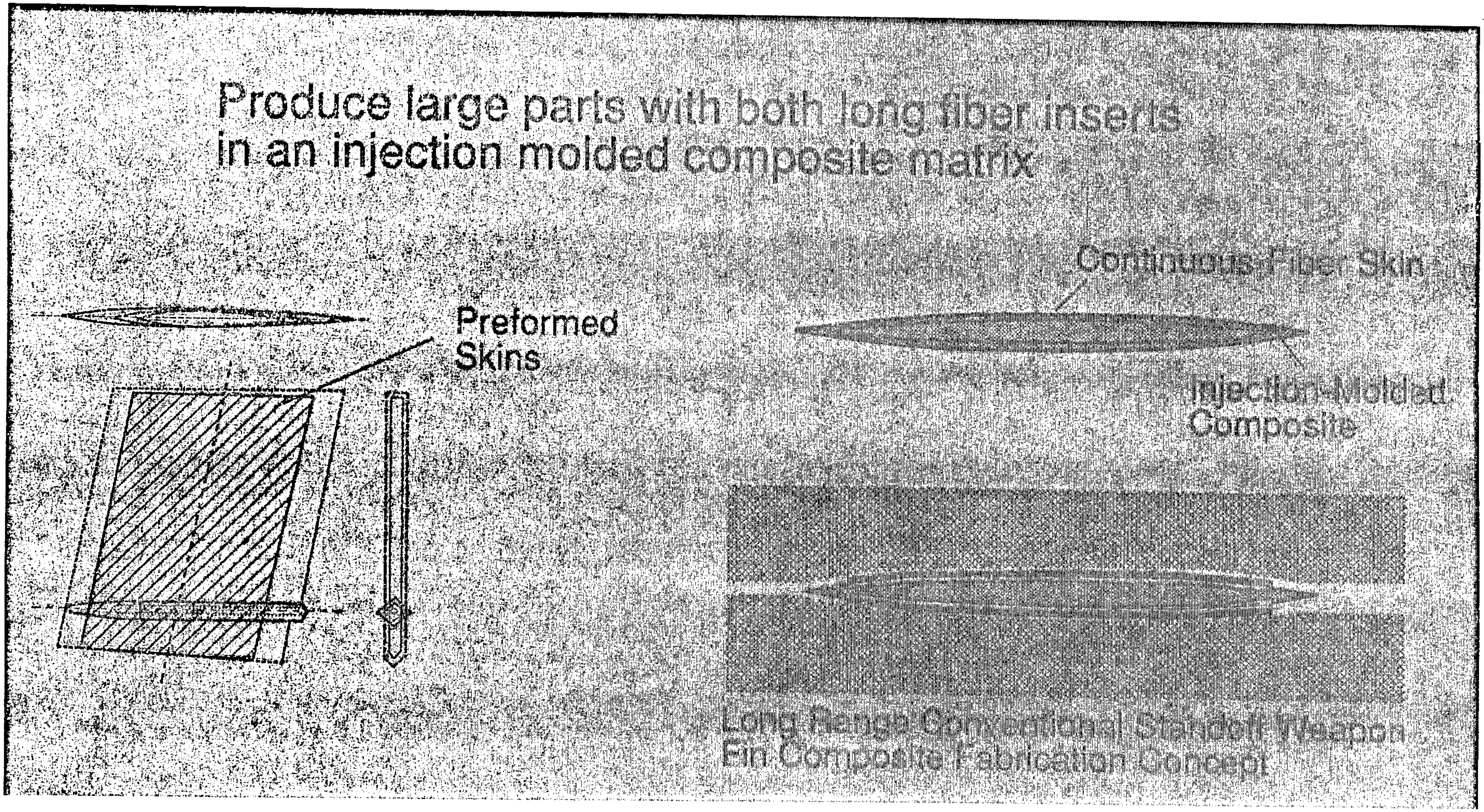
L. Kramer 7/28/83


Metal Structural Fabrication
Metal Turning
Drilling
Install Nutplates
Detail Assembly
Install Fasteners

Thermoplastic Structural Fabrication



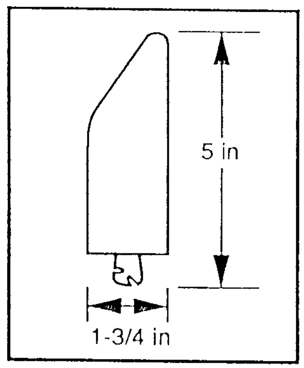
Thermoplastic composite payoffs
- **Less weight**
- **Greater structural efficiency**
- **Lower cost**


Produce large parts with both long fiber inserts
in an injection molded composite matrix
Preformed
Skins
Continuous-Fiber Skin
Injection-Molded
Composite
Long Range Conventional Standoff Weapon
Fin Composite Fabrication Concept

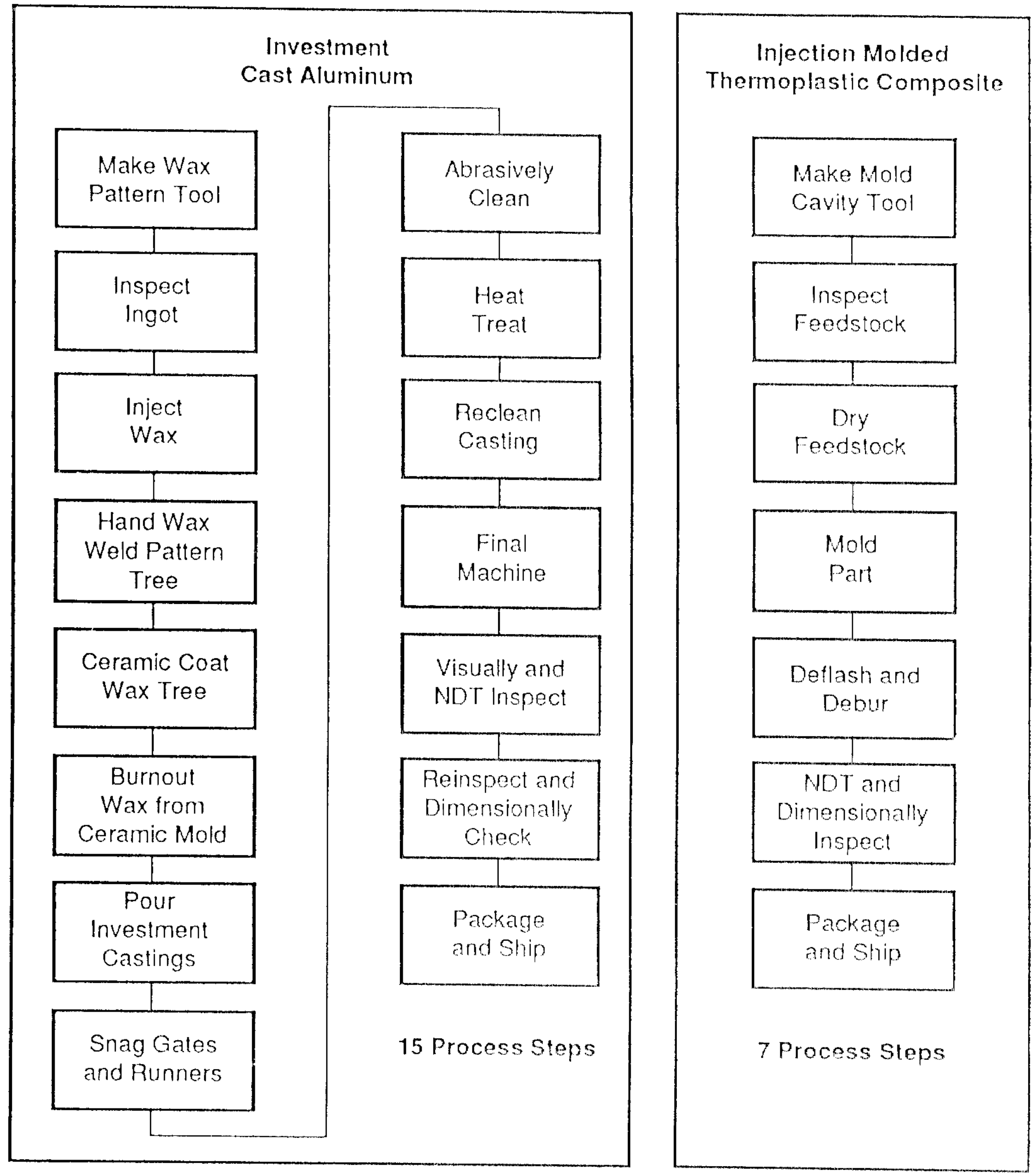
INJECTION MOLDING
NET SHAPE LEADS TO LOW COST

- Flowchart Comparison With Aluminum Investment Casting
- Net Molding Lowers Life Cycle Costs
- Long Fiber Survival in Auger Improves Properties

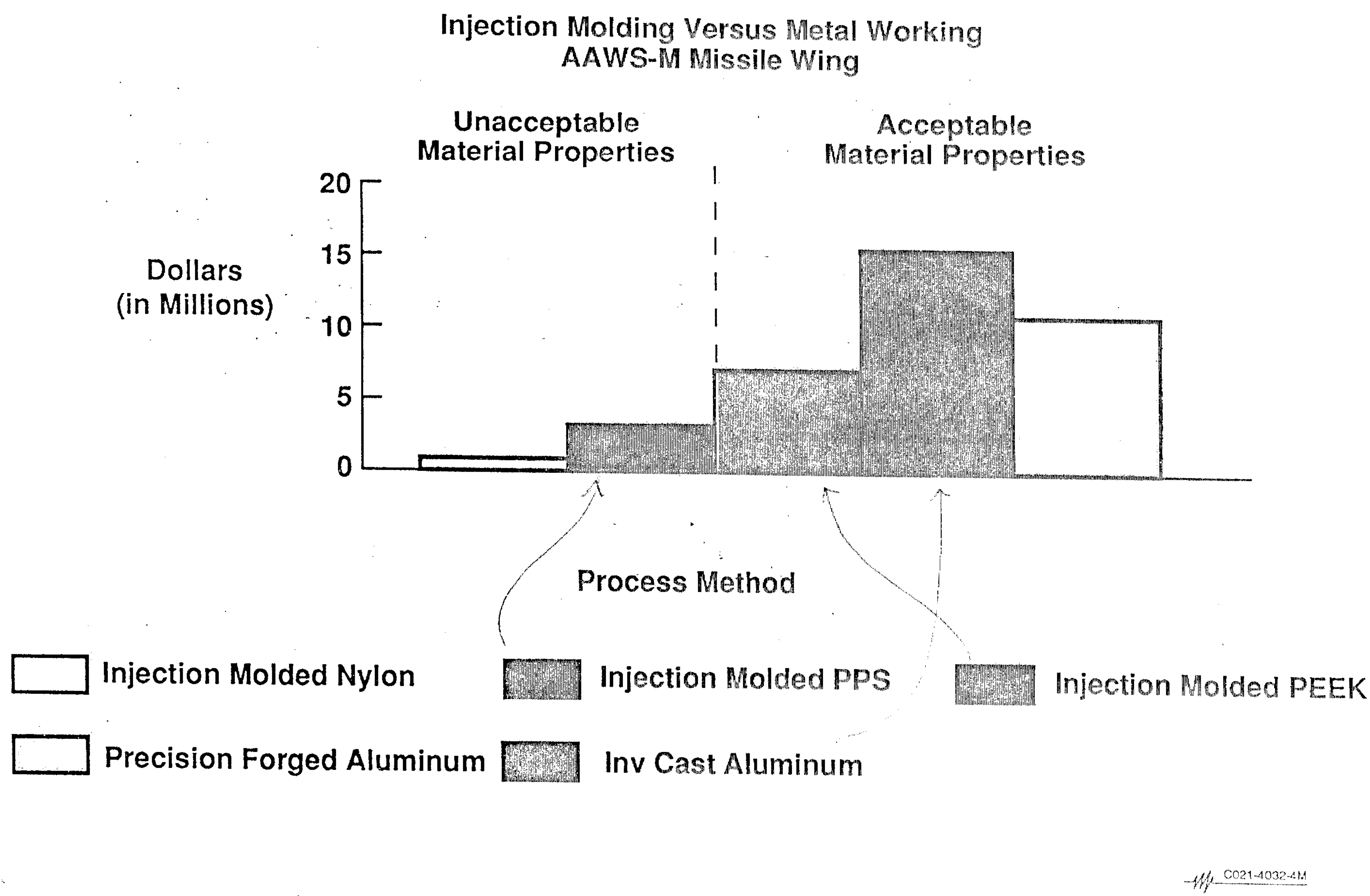
PROCESS FLOWCHART COMPARISON FOR NET SHAPE CONVERSION IN TWO MATERIALS



Generic Missile Wing



TOTAL PROGRAM COSTS



TENSILE PROPERTY BENEFITS FROM OPTIMIZED INJECTION MOLDING TECHNOLOGY FOR CARBON/PEEK COMPOSITES

Material Type	75°F Tensile Strength (KSI)	Percent of A356-T6 Casting Value	Comments
ASTM B618 A356-T6 cast aluminum	34.0	100	Ceramic shell investment casting
30% short carbon fiber/PEEK composite-edge gated	31.5	92.6	Conventional practice
30% short carbon fiber/PEEK composite-edge gated	29.7	87.4	Conventional practice
40% short carbon fiber/PEEK composite-edge gated	33.7	99.1	Conventional practice
40% short carbon fiber/PEEK composite-end gated	30.9	90.9	Conventional practice
40% long 1M-7 fiber/PEEK composite-end gated	41.0	120.6	Long fiber molding technology
50% short IM-7 fiber/PEEK composite-end gated	42.0	123.5	Long fiber molding technology

C021-4032-7

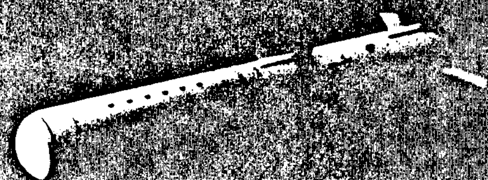
Javelin - A Closed Mold Process Success Story

- Matched Metal Molded Carbon Fiber/ Epoxy Primary Structure
  - Warhead Airframe and Support Cone
  - Guidance Electronics Unit Airframe
- Injection Molded Primary Structure
  - Wings and Fins
  - Internal Bulkheads
  - Guide Vane Supports
  - Battery Cooling Unit/Pylon on Launch Tube
- Injection Molded Secondary Components - Many Circuit Card Supports, Electrical Supports,Etc.

TEXAS INSTRUMENTS

MARTIN MARIETTA

JAVELIN SYSTEM ELEMENTS



ROUND

- 10 YEAR SHELF LIFE
- WOODEN ROUND
- LAUNCH TUBE ASSEMBLY
  - RUGGED DESIGN
  - COMPOSITE CONSTRUCTION
- MISSILE
  - I²R SEEKER (LWIR)
  - ROBUST TARGET TRACKER
  - TANDEM WARHEAD
  - SOFT LAUNCH FEATURE
  - MINIMUM SIGNATURE

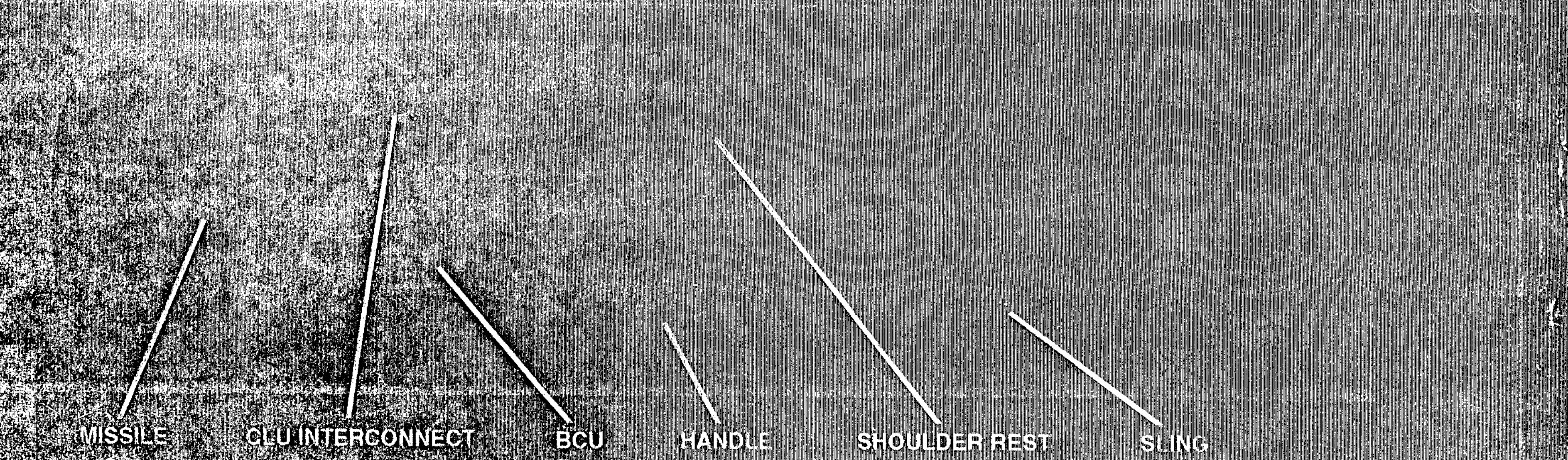
CLU

- INTEGRATED DAY/ THERMAL SIGHT
  - 4X DAYSIGHT
  - DUAL FOV LWIR FLIR
  - 4 HOUR BATTERY OPERATION
  - BIT
- SIMPLE OPERATION
- RUGGED/LIGHTWEIGHT
- HIGH RELIABILITY DESIGN

FIRE & FORGET

223105ML

JAVELIN ROUND DESCRIPTION



DESCRIPTION:
Fire & Forget Missile in a disposable Launch Tube with CLU interface, replaceable Battery/Coolant Unit (BCU), removable Endcap, Carry Handle and adjustable Shoulder Strap.

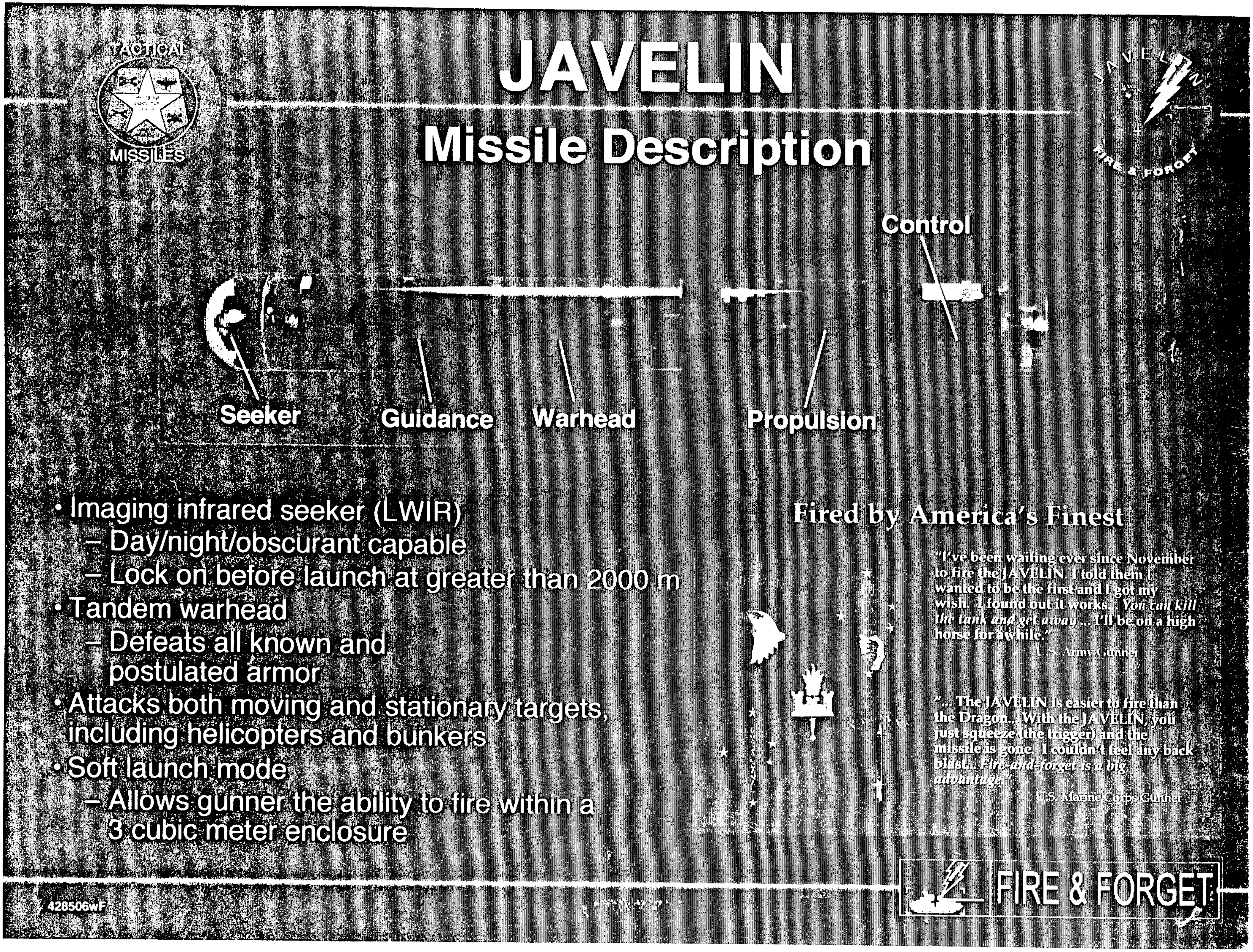
FEATURES:
- MANPRINT OPTIMIZED
  - SYSTEM/OPERATOR INTERFACE
  - SAFETY
  - TRAINING
- MAINTAINABILITY
  - WOODEN ROUND CONCEPT
  - 10 YEAR SHELF LIFE
  - GO/NO GO BIT
- NBC/EMI HARDENED

PORTABILITY

FIRE & FORGET

C-40

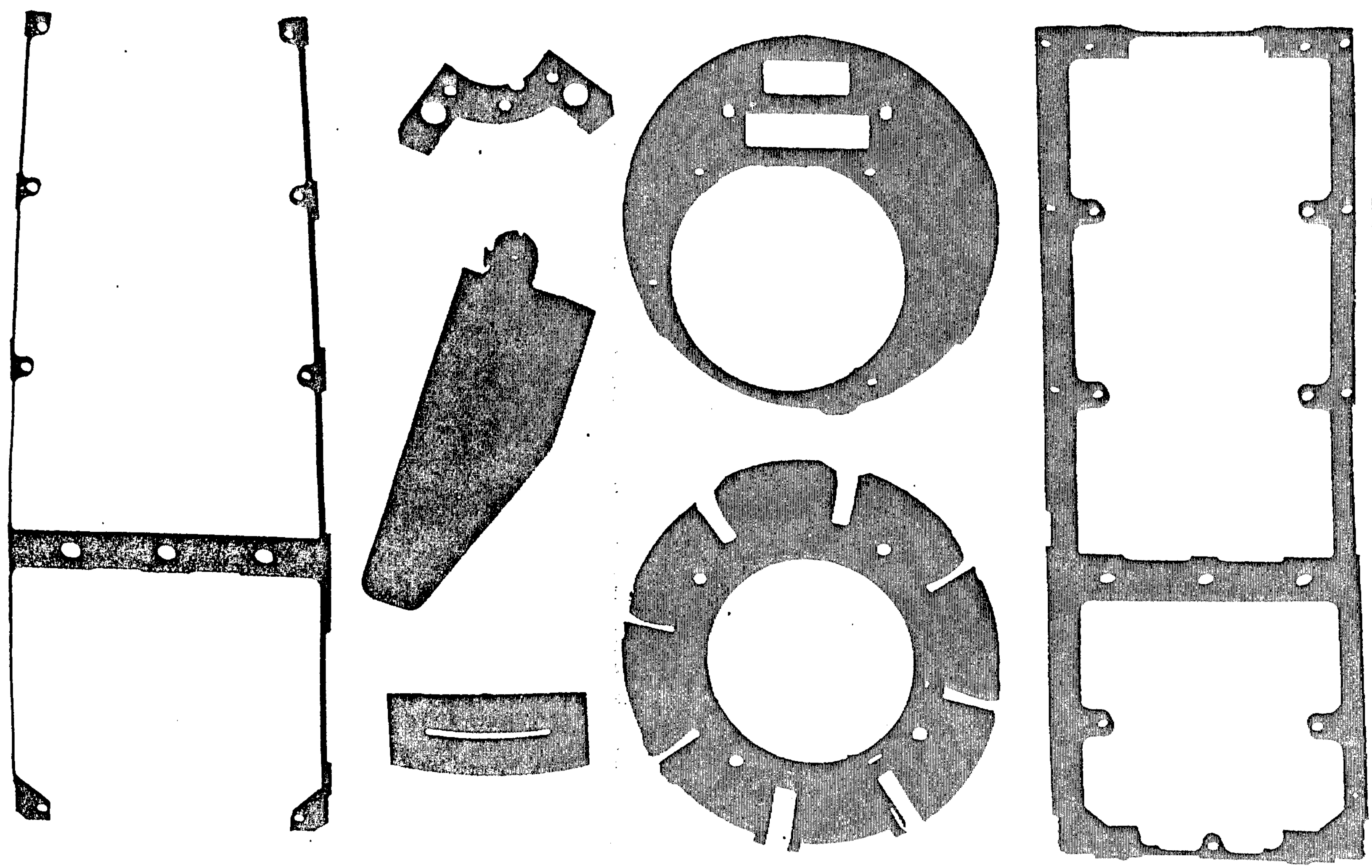
101MI


TACTICAL MISSILES
JAVELIN
Missile Description
JAVELIN FIRE & FORGET
Seeker
Guidance
Warhead
Propulsion
Control
• Imaging infrared seeker (LWIR)
– Day/night/obscurant capable
– Lock on before launch at greater than 2000 m
• Tandem warhead
– Defeats all known and postulated armor
• Attacks both moving and stationary targets, including helicopters and bunkers
• Soft launch mode
– Allows gunner the ability to fire within a 3 cubic meter enclosure
Fired by America's Finest
"I've been waiting ever since November to fire the JAVELIN. I told them I wanted to be the first and I got my wish. I found out it works... You can kill the tank and get away ... I'll be on a high horse for awhile."
U.S. Army Gunner
"... The JAVELIN is easier to fire than the Dragon... With the JAVELIN, you just squeeze (the trigger) and the missile is gone. I couldn't feel any back blast... Fire-and-forget is a big advantage."
U.S. Marine Corps Gunner
FIRE & FORGET
428506wF

JAVELIN - LESSONS LEARNED

- Matched Metal Mold Experience
  - Excellent Replication of Complex Shapes
  - Net Shape Wing Slots
  - Much Cutting and Placement
  - Wrinkles and Porosity
- Injection Molded Parts
  - Gate for Fiber Alignment
  - Tolerance Control (i.e., Packing, Mold Hold Time, etc.)
  - Survival of Fiber in Auger Key to Properties
  - Rapid Prototyping of Molds

Injection Molded TPC Parts



MARTIN MARIETTA

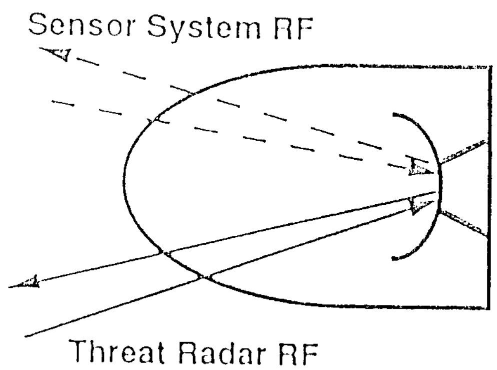
CD91-4296-42

LONGBOW MISSILE & FIRE CONTROL RADAR - CLOSED MOLD METHODS REDUCE COST

- System Overview - Missile & Radar
- Injection Molded Composites in Missile
- Closed Mold Methods for Adsorptive Missile Radome
- Fire Control Radar Mast Mounted Assembly (MMA)
  - Injection Molded Details
  - RTM'd Hub

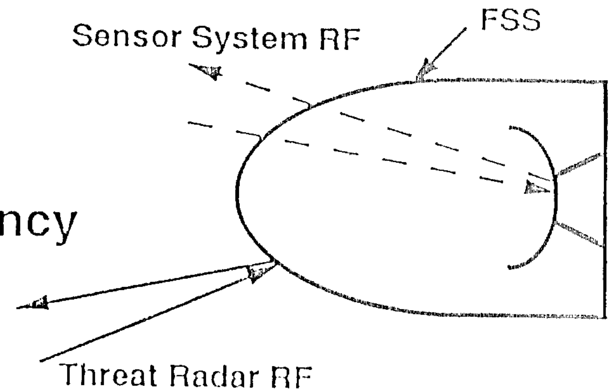

31

Absorptive Radome Concept



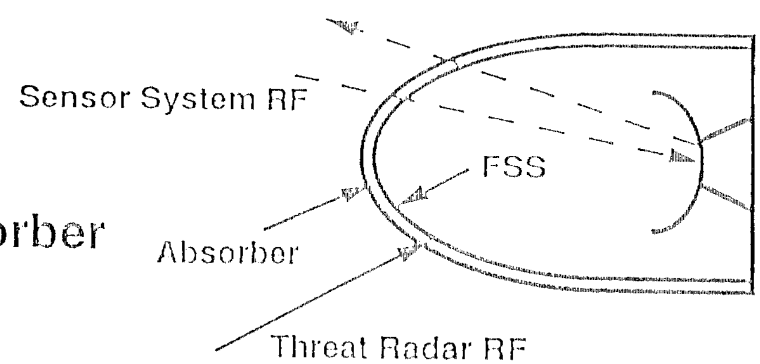
Problem: Radome is RF-transparent, so threat "sees" antenna/bulkhead through it.

1st Approach:
Add Frequency Selective Surface



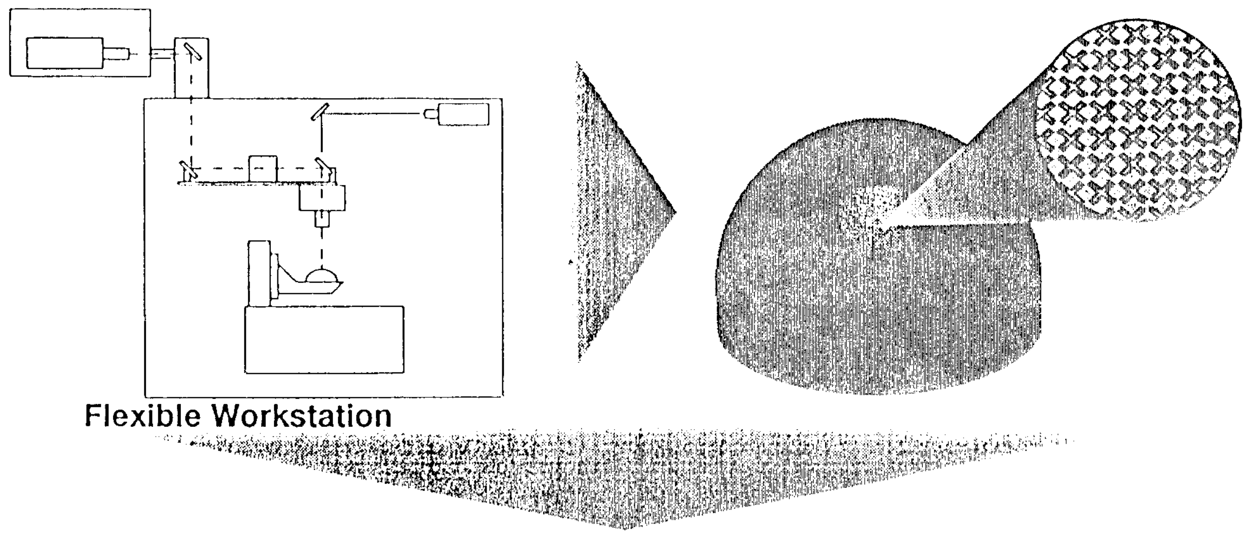
Problem: If radome is "wrong" shape, echo is still large.

Solution:
Add RF Absorber to FSS

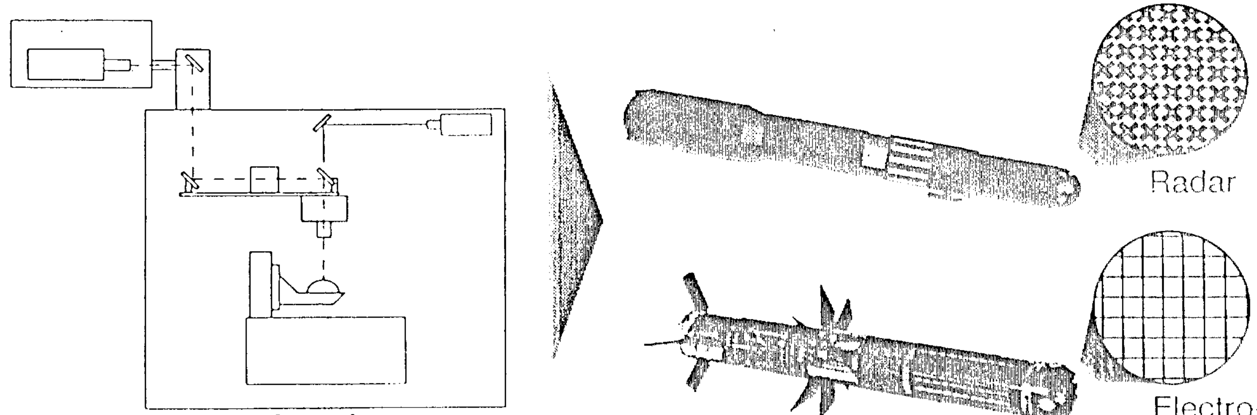


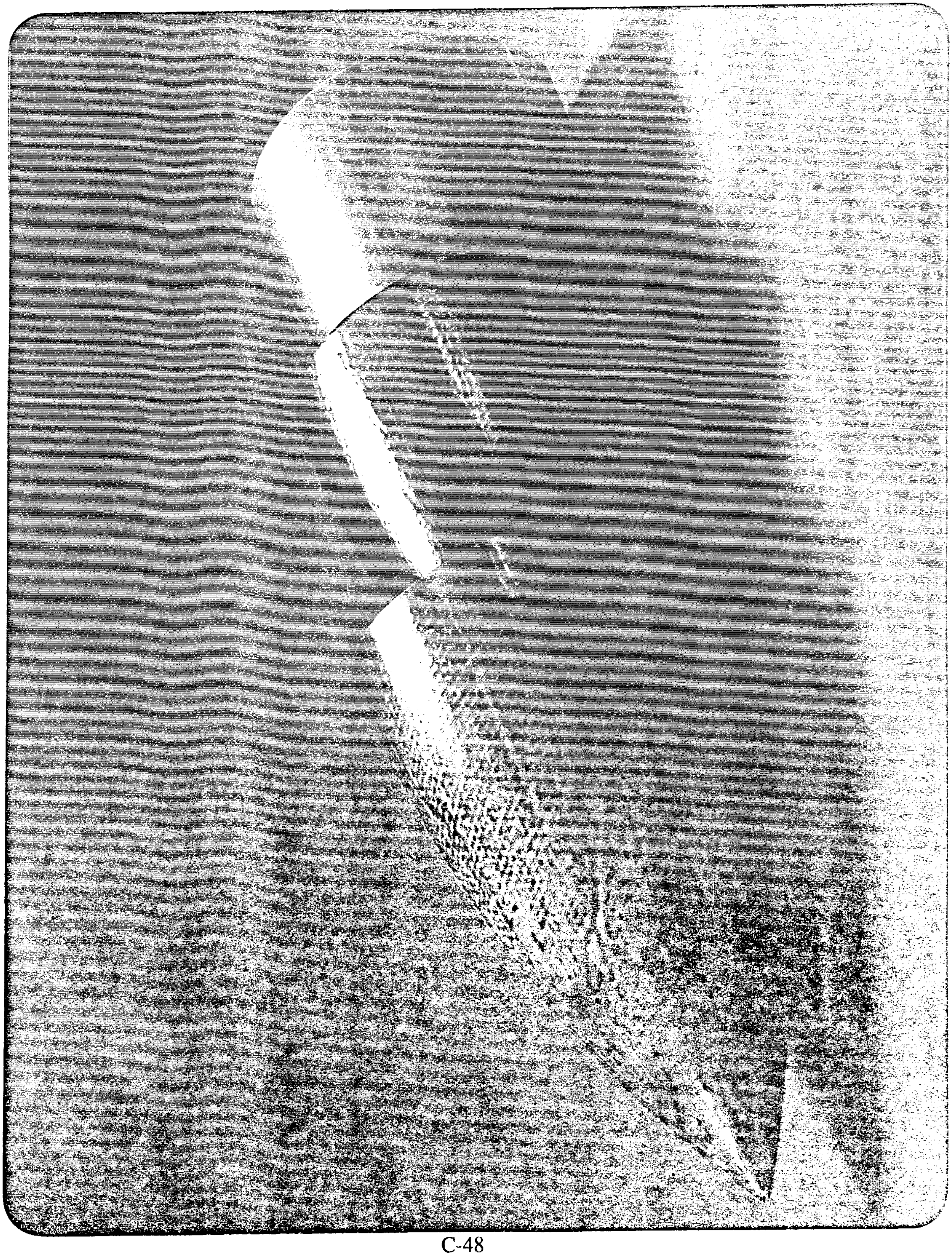
Advanced Manufacturing Methods for EMI Shielding

- Today's success – Advanced state-of-the-art manufacturing methods

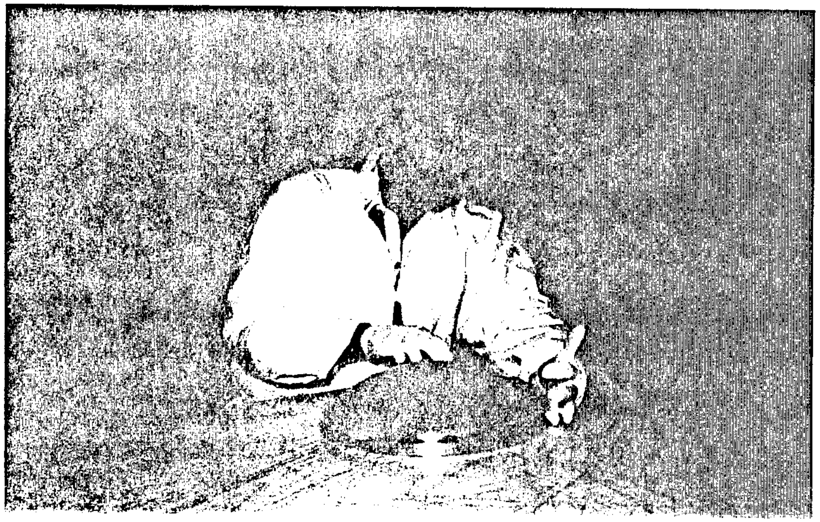


- Tomorrow's success – Advanced state-of-the-art manufacturing methods
  – Reduced production time to <1 hour

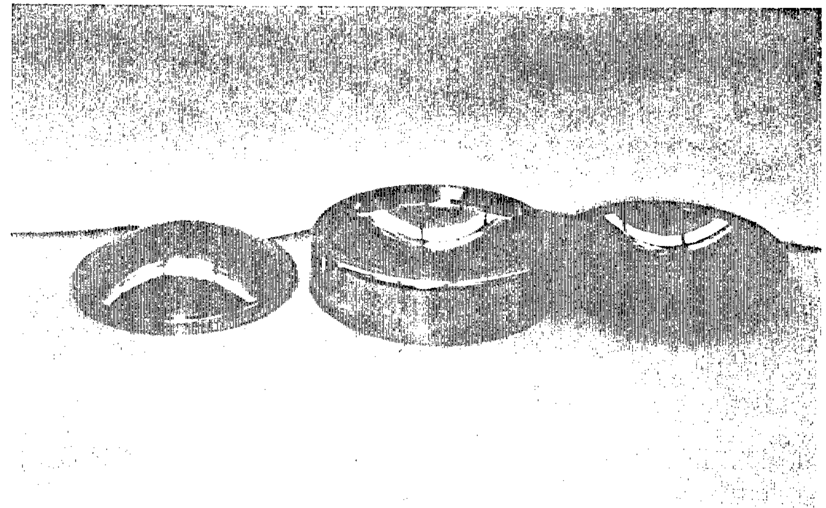




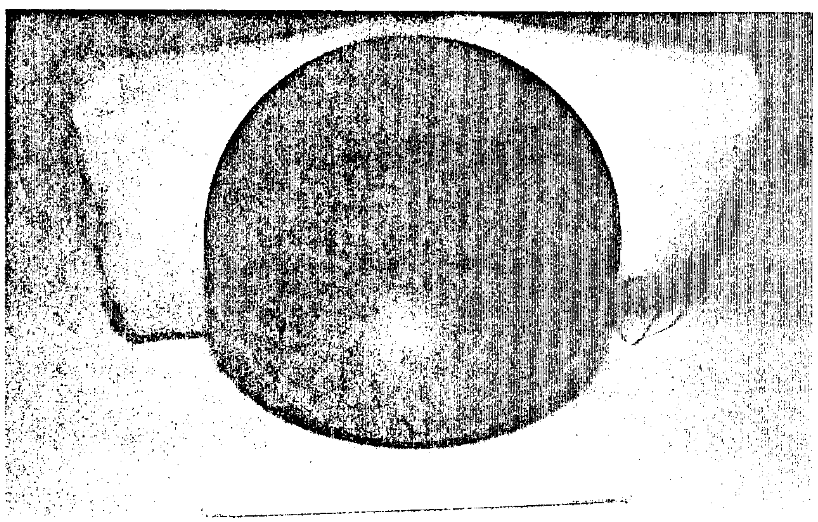
FSS REFLECTOR FABRICATION



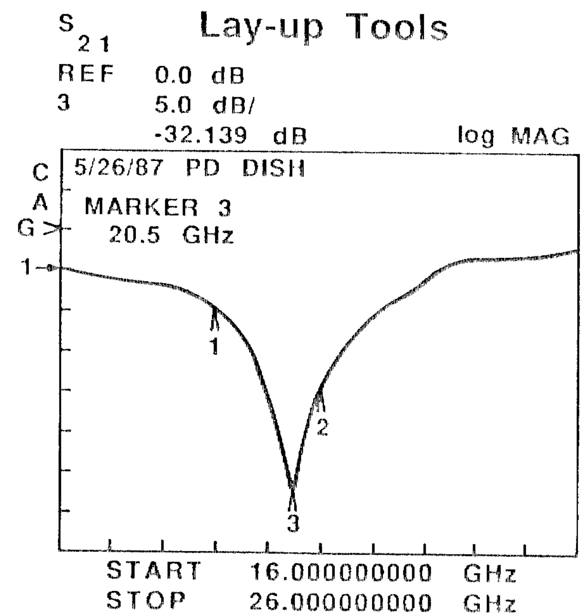
Composite Fabrication



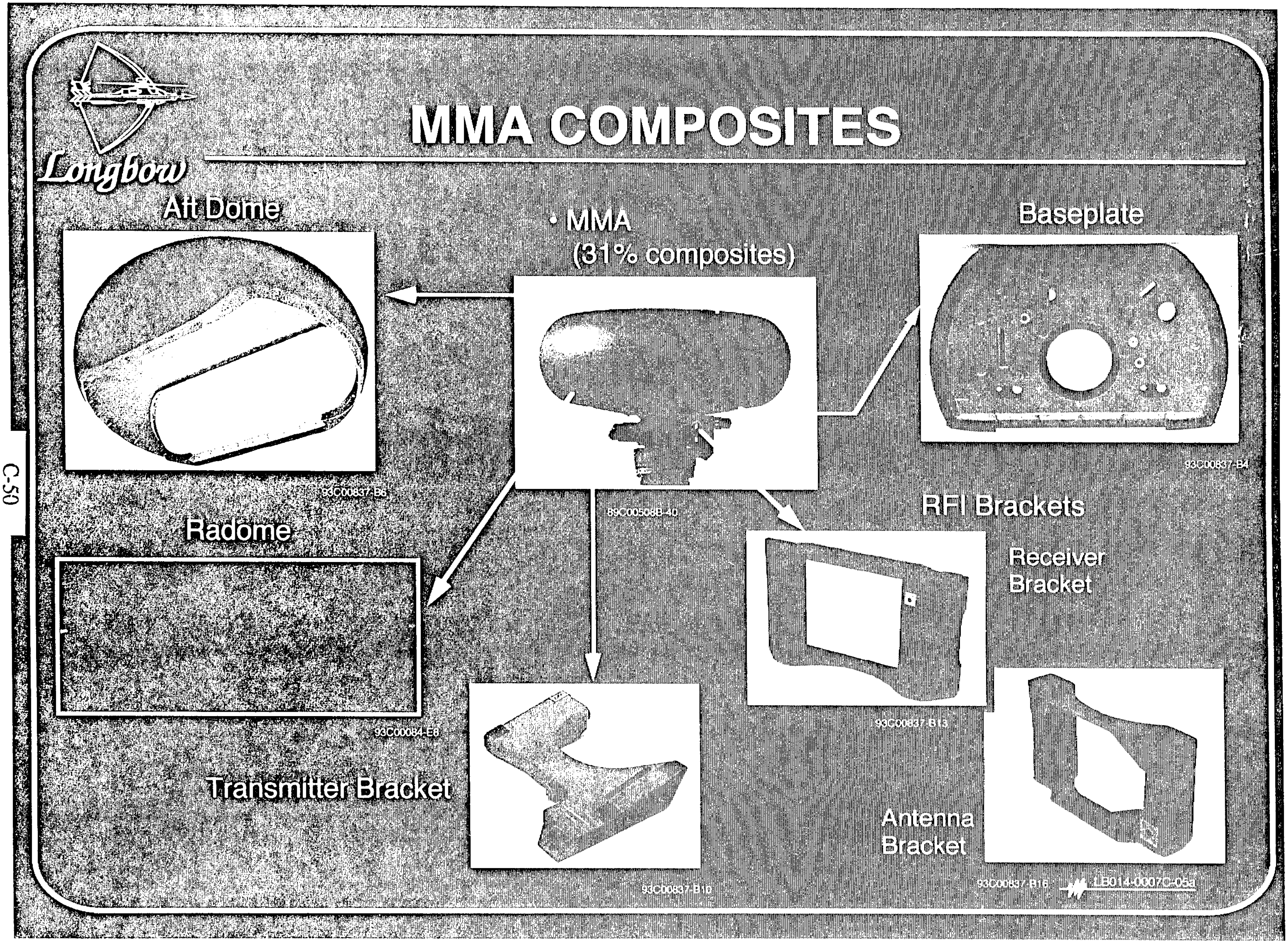
Lay-up Tools

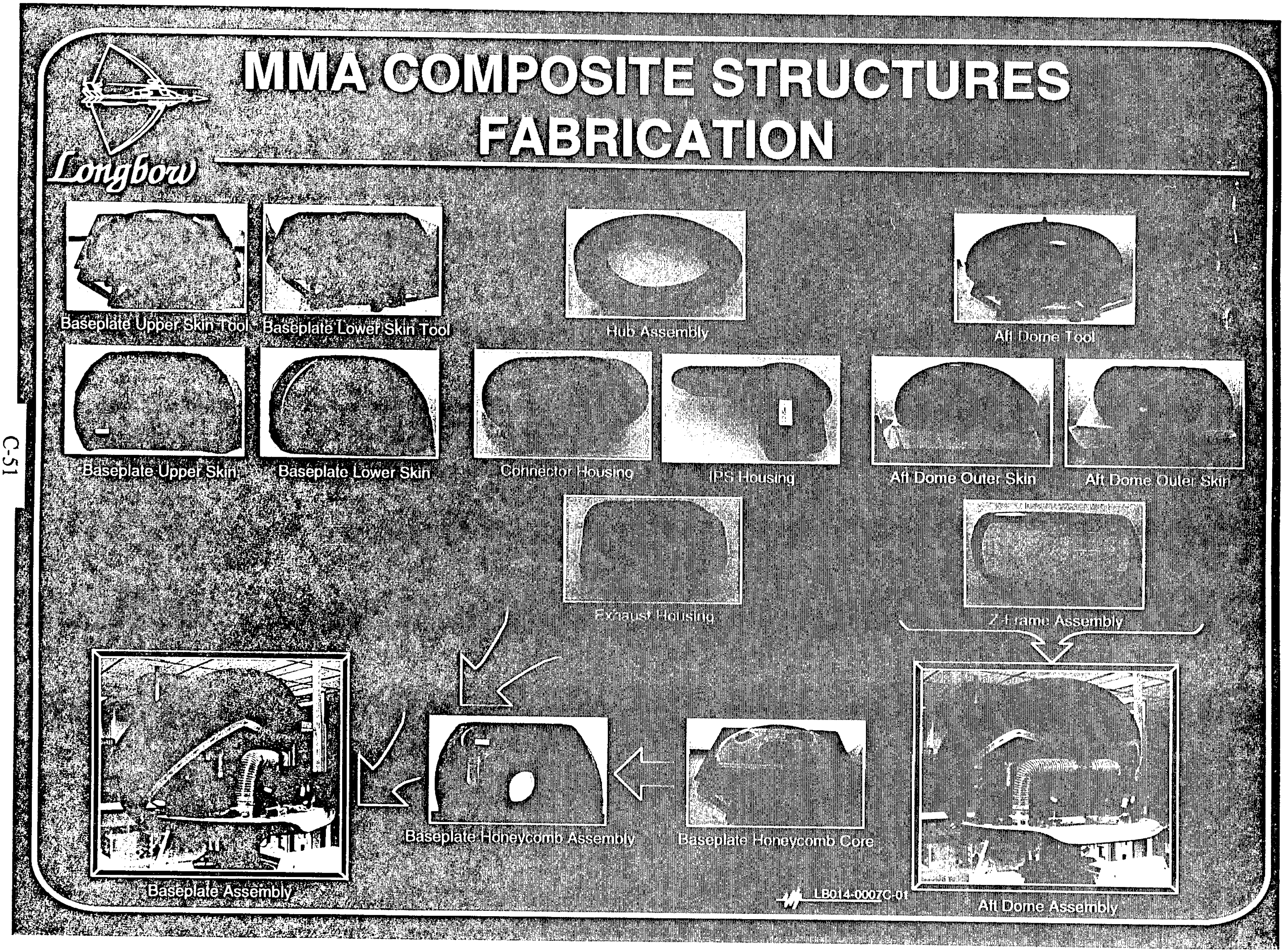


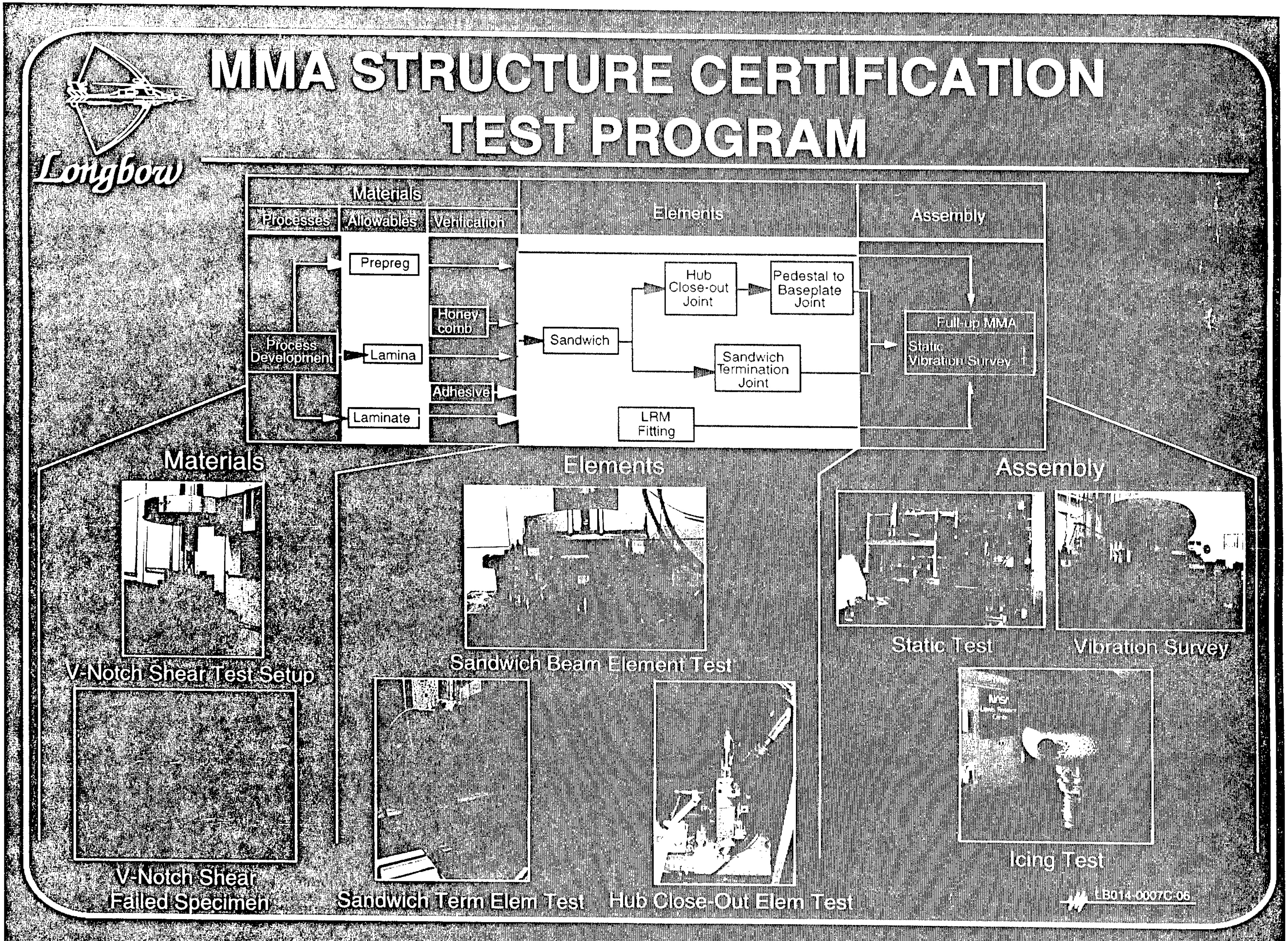
Finished Antenna Dish



Measured Data


Longbow
MMA COMPOSITES
Aft Dome
• MMA
(31% composites)
Baseplate
93C00837-B6
89C00508B-40
93C00837-B4
Radome
RFI Brackets
Receiver
Bracket
93C00084-E8
93C00837-B13
Transmitter Bracket
Antenna
Bracket
93C00837-B10
93C00837-B16
LB014-0007C-05a


MMA COMPOSITE STRUCTURES
FABRICATION
Longbow
Baseplate Upper Skin Tool
Baseplate Lower Skin Tool
Hub Assembly
Aft Dome Tool
Baseplate Upper Skin
Baseplate Lower Skin
Connector Housing
IPS Housing
Aft Dome Outer Skin
Aft Dome Outer Skin
Exhaust Housing
Z-Frame Assembly
Baseplate Honeycomb Assembly
Baseplate Honeycomb Core
Baseplate Assembly
LB014-0007C-01
Aft Dome Assembly



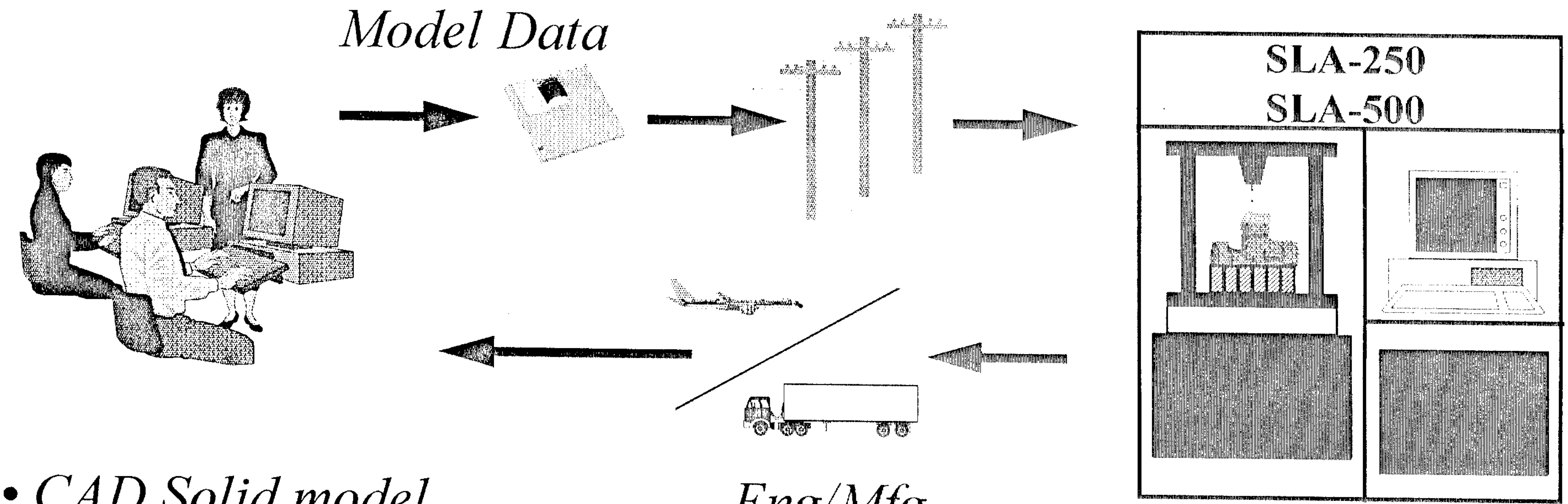
Longbow
MMA STRUCTURE CERTIFICATION
TEST PROGRAM
Materials
Processes
Allowables
Verification
Elements
Assembly
Prepreg
Process Development
Lamina
Laminate
Honey comb
Adhesive
Sandwich
Hub Close-out Joint
Pedestal to Baseplate Joint
Sandwich Termination Joint
LRM Fitting
Full-up MMA
Static Vibration Survey
Materials
V-Notch Shear Test Setup
V-Notch Shear Failed Specimen
Elements
Sandwich Beam Element Test
Sandwich Term Elem Test
Hub Close-Out Elem Test
Assembly
Static Test
Vibration Survey
Icing Test
LB014-0007C-06

Other R's - Rapid Prototyping, RTM Simulation, and Recycling

- Rapid Prototyping of Tooling and Composite Parts
  - Direct Generation of Tooling
  - Fit Check of Composite Parts
- Recycling of Thermoplastics
- RTM Simulation Program
  - 486 PC Based
  - Takes into Account
    - Vent Opening
    - Resin Viscosity
    - Weave Porosity

Rapid Prototyping - "Art to Part"

Lockheed Martin



- CAD Solid model
- Design / Mfg.

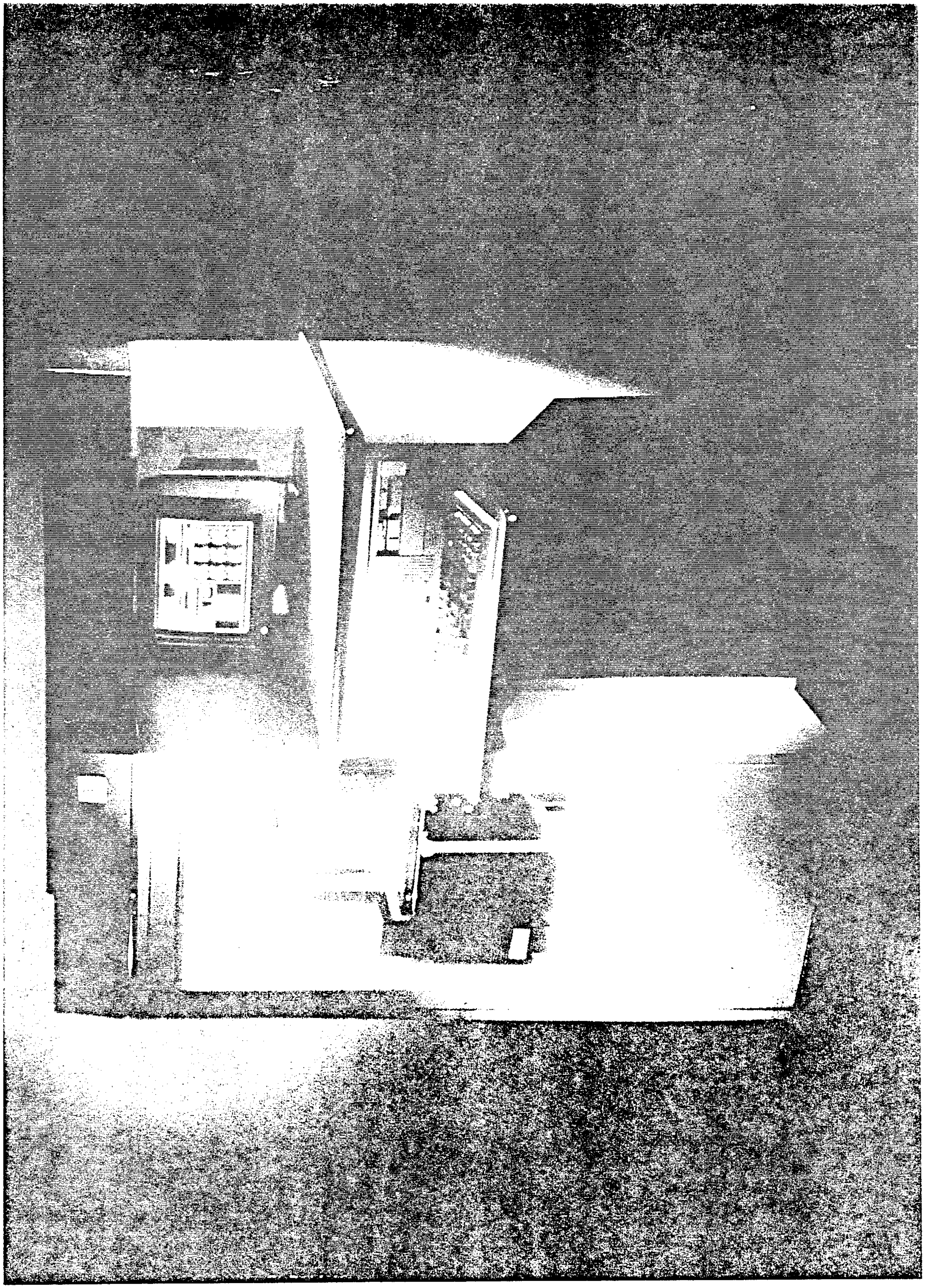
Eng/Mfg
Prototype
Model

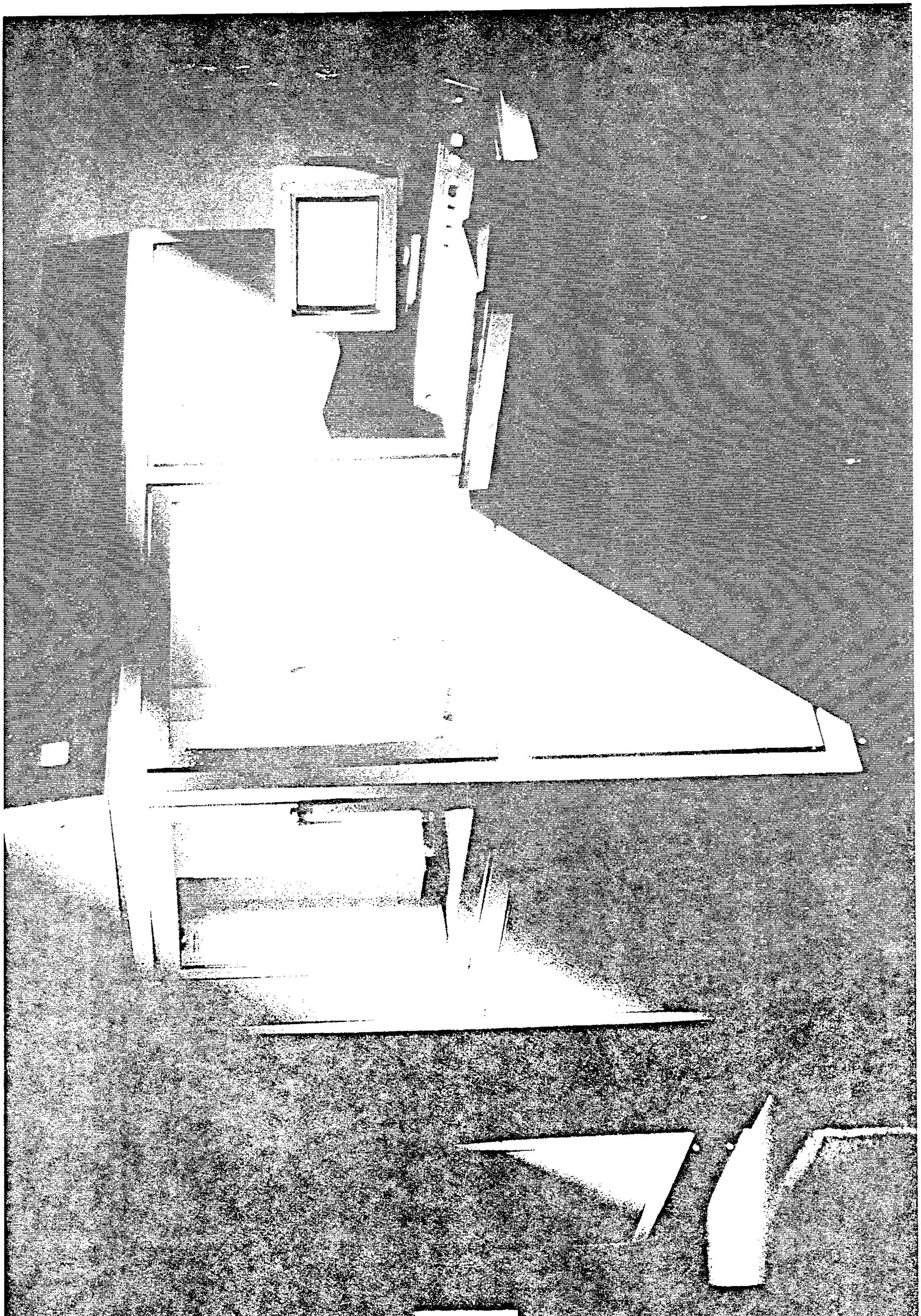
E&M
RP LAB

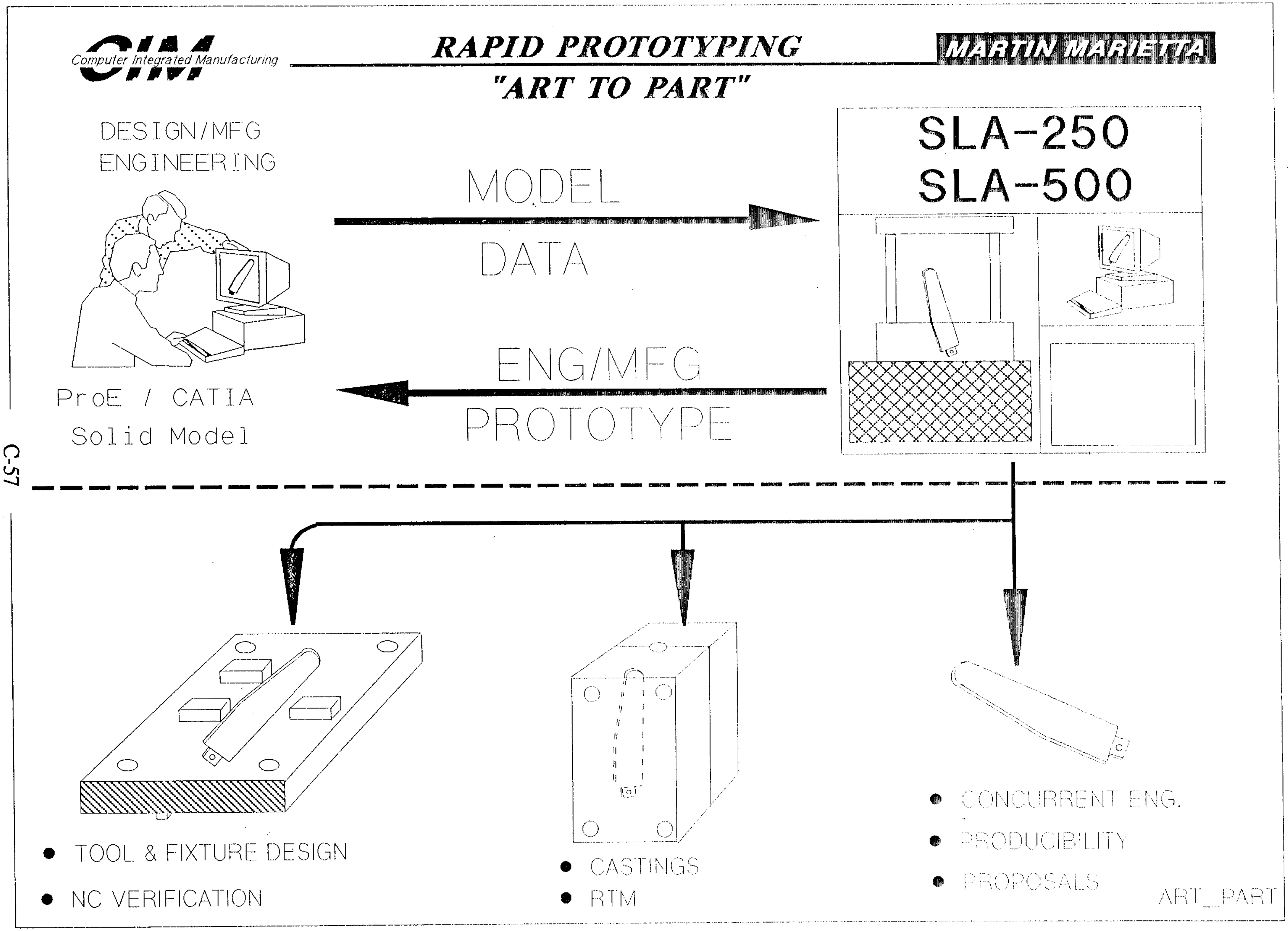
Tool & Fixture Design
Fit-Checking
NC Validation
Castings

Concurrent Engineering
Producibility / Maintainability
Proposals / Marketing

BMP1.PPT







Computer Integrated Manufacturing
RAPID PROTOTYPING
"ART TO PART"
MARTIN MARIETTA
DESIGN/MFG
ENGINEERING
MODEL
DATA
SLA-250
SLA-500
ENG/MFG
PROTOTYPE
ProE / CATIA
Solid Model
• TOOL & FIXTURE DESIGN
• NC VERIFICATION
• CASTINGS
• RTM
• CONCURRENT ENG.
• PRODUCIBILITY
• PROPOSALS
ART_PART

Rapid Prototyping - Benefits

Lockheed Martin

- ALLOWS EARLY DESIGN REVIEWS........ENG/MFG/IPTs,Proposals
- MORE ITERATIONS....................................3 - 5+ VS. 1 - 2
- REDUCED CYCLE TIMES..........................24 HRs to 1 - 3 Weeks
- REDUCED DESIGN ERRORS......................Catch errors using physical part
- PRODUCIBLE PARTS................................ Tool & Machine Access
- INTEGRATED WITH DFx............................Validate DFx Analysis
- VALIDATE NC TOOL PATHS.................. Check Physical Parts (No Chips)
- RAPID ACQUISITION OF CASTINGS ....3 Week Casting Process
- CABLE-WIRE-HARNESS DESIGN............. Fits & Harness Boards
- ASSEMBLY VALIDATION..........................Complex Assy's Reviewed Early
- ALLOWS PAPERLESS DEVELOPMENT.....Transfer CAD/SLA Models
- IMPROVES COMMUNICATION...................Early Vendor Reviews / Quotes
- INTEGRATES QUALITY INSPECTION.........CMM Inspection w/o Drawings

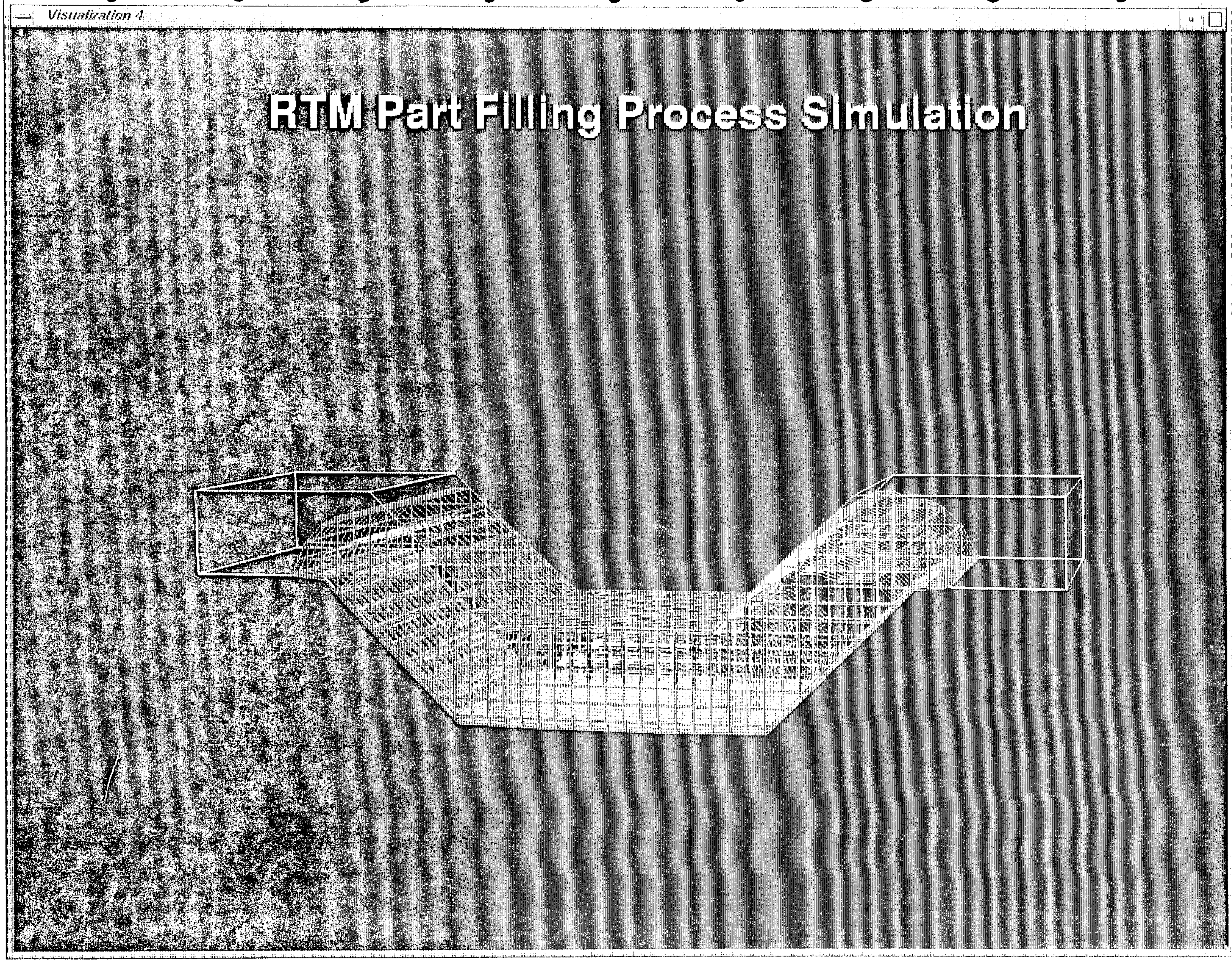
BMP1.PPT

Current RTM Issues

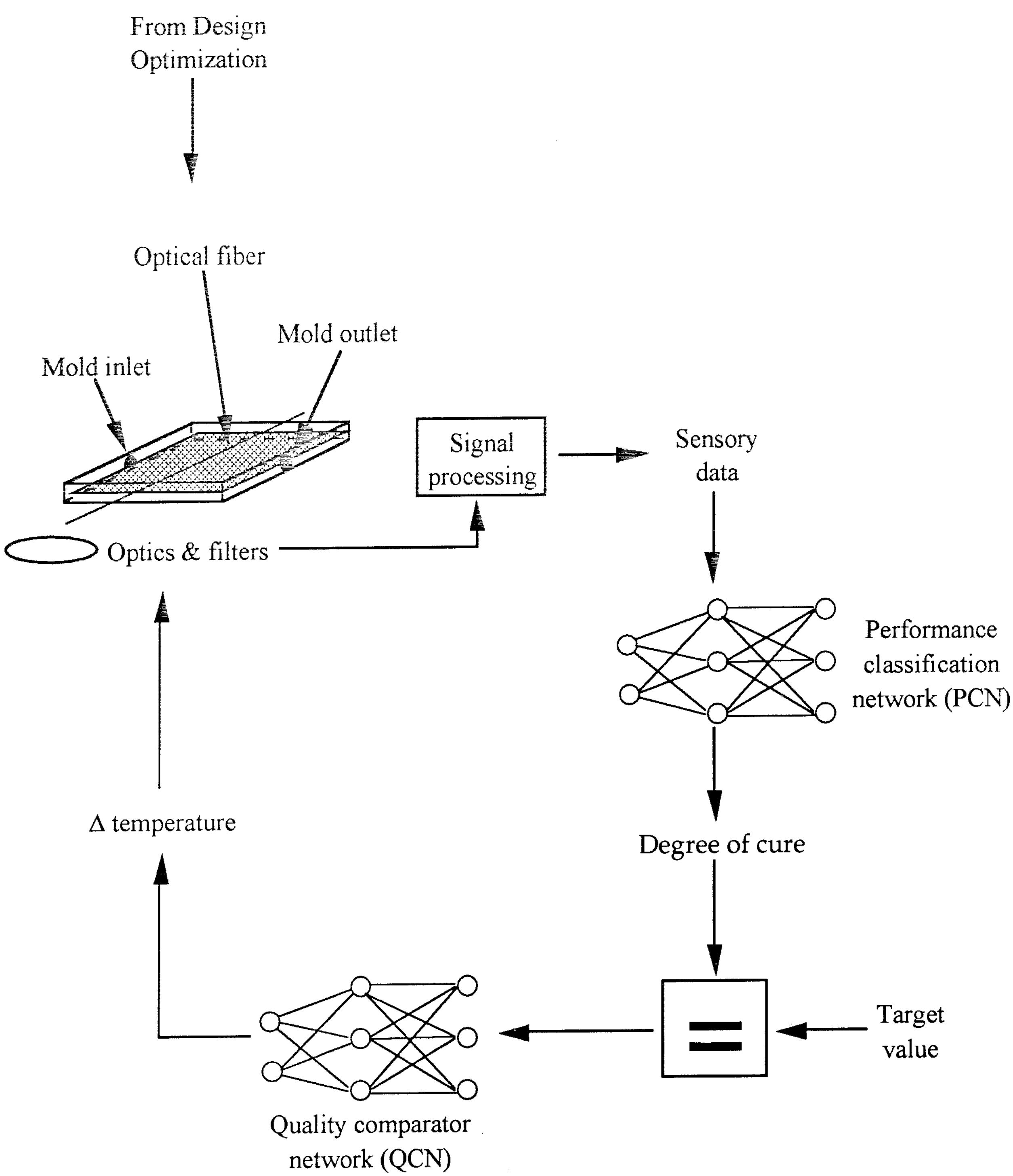
- Manufacturing of composites lacks a firm scientific basis.
  - « Tooling, preform design and process development conducted on a trial-and-error basis.
  - « Part quality is often inadequate.
  - « Lack of part-to-part reproducibility.

Process Performance Prediction with Neural Networks

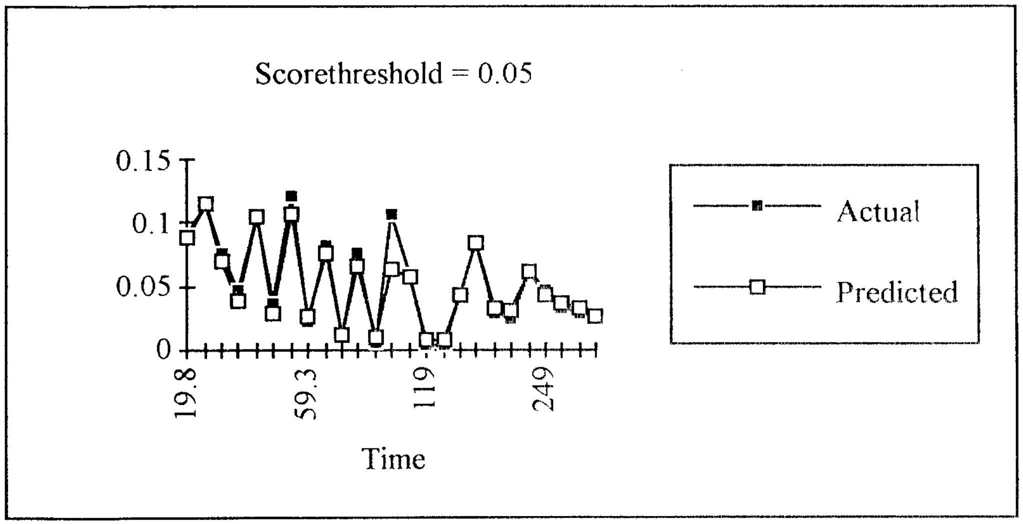
- Nonlinear, complex relationship between processing variables and process performance
- A large number of resin and fiber combinations
- Cascade Correlation Algorithm

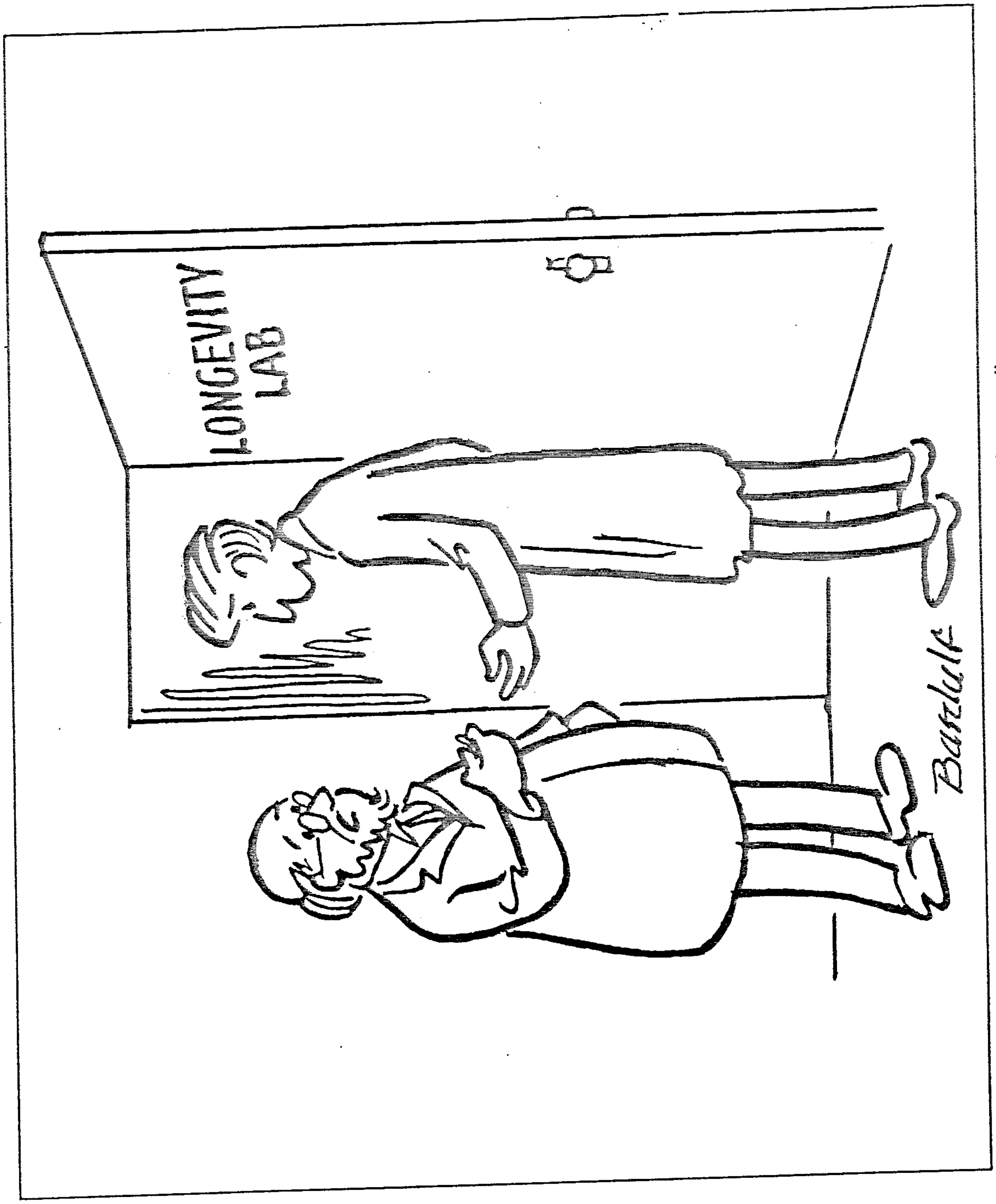

Visualization 4
RTM Part Filling Process Simulation

Process Control Scheme



Actual vs. Predicted % Monomer





"Take two of these and call me a century from now."

Recycling AS-4/APC-2 Thermoplastic Scrap Yields Secondary Processed Feedstock with Excellent Mechanical Properties

Product Form	Tensile Strength (ksi)	Flexural Modulus (msi)	Comments
Virgin thermoplastic unidirectional tape prepreg	102	6.5	Starting precursor material
Chipboard chopped squares (1 to 2 inches/side)	53	5.5	Compression molded
Long fiber (3/8 inch long) injection molding compound (Verton™ VUHM)	40	5.0	Experimental
Short fiber injection molding compound (UHM)	34	3.0	Experimental
Commercial injection molding compound (150 CA 30/40)	33	2.9	

MARTIN MARIETTA

C061-4199-31

CLOSING COMMENTS

- Martin Marietta Utilizes Extensive Closed Mold Composites Fabrication
- Tactical Missiles Demand Net Shape Composites Fabrication to Hold Cost Down
- Injection Molding and Matched Metal Molding Have Had the Greatest Impact in Meeting Customer
- As We Improve Simulation Tools, We are Moving Toward Structural RTM
- Rapid Prototyping Use for Composite Part Simulation and Tooling Concepts Are Increasing Every Year

ADVANCED POLYMER COMPOSITES IN MISSILE SYSTEMS

GOVERNMENT/ INDUSTRY WORKSHOP ON CLOSED-MOLD MANUFACTURING OF HIGH PERFORMANCE COMPOSITES MISSILE STRUCTURES

ROSS RINGWALD

15 MAY 1995

HUGHES

HUGHES MISSILE SYSTEMS COMPANY

ADVANCED POLYMER COMPOSITES IN MISSILE SYSTEMS

HUGHES

HUGHES MISSILE SYSTEMS COMPANY

TOPICS

- CHIEF ENGINEERS CONCERNS
- PROGRAM OFFICE VISION
- APPLICATIONS IN GENERAL
- FOCUS FOR COMPOSITES
- PROPERTIES OF INTEREST
- STANDARDIZED MATERIALS TEST DATA

ADVANCED POLYMER COMPOSITES IN MISSILE SYSTEMS

HUGHES

HUGHES MISSILE SYSTEMS COMPANY

CHIEF ENGINEER'S CONCERNS ABOUT COMPOSITES

- MEETING DEVELOPMENT SCHEDULES
- PASSING QUALIFICATION TESTING
- CONSISTENCY IN QUALITY AND STRENGTH
- HIGH TEMPERATURE USAGE (> 800 deg F)
- FUEL / FLUIDS COMPATIBILITY
- INTERCHANGEABILITY (CONVERSIONS)
- DAMAGE TOLERANT /REPAIRABILITY
- JOINING / LOADS TRANSFER

  BOLT HOLES

  BONDING.

PROGRAM OFFICES VISION

PERFORMANCE
- STRENGTH / WEIGHT
- STEALTH

QUALITY
- TAILOR SYSTEM TO CUSTOMER DESIRES
- PROVIDE SERVICE LIFE USEFULNESS

COST REDUCTION
- COMBINE FEATURES / REDUCE ASSEMBLY TIME
- INTEGRATE SYSTEM / STRUCTURE/TUBES/WIRES
- CONTINUE TO MAKE COST REDUCTIONS

SCHEDULE
- REALISTIC / RISK MITIGATION
- RESPONSIVE

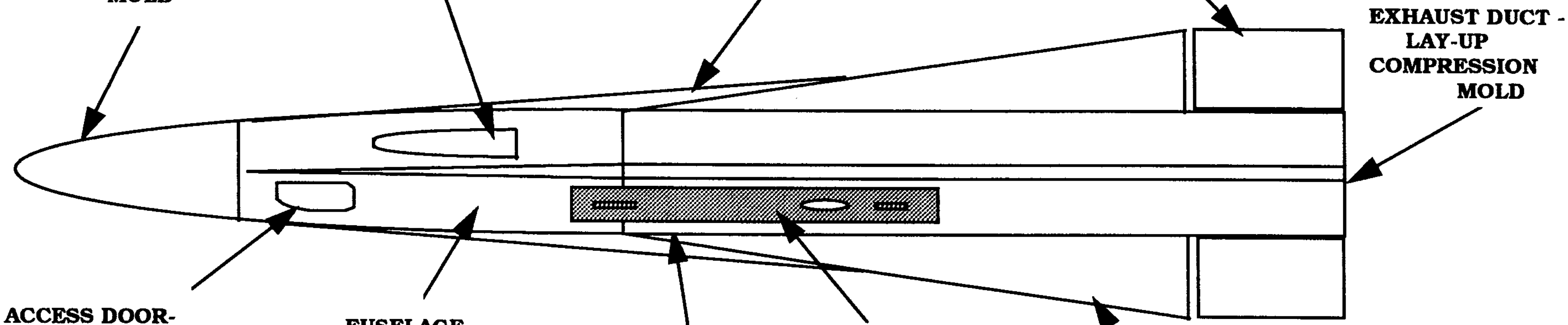
PROPERTIES OF INTEREST

- TEMPERATURE / TIME
  - -65 to +180 / 6 HR CARRY,
  - +400 DASH / 3-4 HR , +1000 FLIGHT/ 2 MIN
- PERMEABILITY
  - AIR / MOISTURE SEALING
  - LAUNCHER (EXAMPLE) - 4.1 CC/HR OF AIR
- JOINT STRENGTH
  - FASTENERS - RELAXATION / TEAR OUT
  - BONDING - PROOF TESTS
- ENVIRONMENTAL
  - FLUIDS - HYDRAULICS, DE-ICING, FUELS, SOLVENTS
  - HOT / WET CONSIDERATIONS
- DURABILITY
  - FATIGUE
  - IMPACT DAMAGE TOLERANCE

ADVANCED POLYMER COMPOSITES IN MISSILE SYSTEMS

HUGHES MISSILE SYSTEMS COMPANY

APPLICATIONS IN GENERAL WITH OPEN MINDS



- •EJECTABLE PROTECTIVE COVERS
  RTM, LAY-UP, COMPRESSION MOLD
- •GROUND SUPPORT EQUIPMENT
  RTM, COMPRESSION MOLD, LAY-UP

4

ADVANCED POLYMER COMPOSITES IN MISSILE SYSTEMS

HUGHES

HUGHES MISSILE SYSTEMS COMPANY

SUGGESTED FOCUS FOR COMPOSITES

- AGILE / LOW RATE MANUFACTURING
  - PROVIDE VERSATILE TOOLING
  - MANUFACTURING PROCESSES
- DESIGN / MAINTENANCE
  - TAILORABLE SYSTEMS I.E. COMBINED MATERIALS
  - REPAIR SYSTEMS / TECHNIQUES
- CONTINUED NEEDS
  - STIFFNESS / STRENGTH DATA
  - THERMAL / ELECTRICAL DATA

STANDARDIZED MATERIALS TEST DATA

- DEVELOP CONFIDENCE IN MATERIALS DATA
- STANDARDIZE TYPE AND METHODS OF MATERIALS TESTING TO EASILY SHARE MATERIAL AND DESIGN DATA

EXAMPLE:

AUTOMOTIVE COMPOSITES CONSORTIUM

GM / FORD / CHRYSLER

GOALS:

AN AUTOMOTIVE DATABASE FOR STRUCTURAL ANALYSIS CONTAINING COMPARABLE DESIGN INFORMATION

DEVELOPMENT OF TEST METHODS AND AN INFORMATION BASE RELATED TO DURABILITY

CONCLUSIONS

- GENERAL CONFIDENCE EXISTS IN COMPOSITES FOR HIGH STRENGTH / HIGH STIFFNESS / LOW WEIGHT APPLICATIONS
- TECHNICAL CONCERNS ARE BASED ON ENVIRONMENT EFFECTS, INTEGRATION, AND SCHEDULE PERFORMANCE
- LOWER COST LOW RATE APPROACHES TO COMPOSITE SYSTEMS NEED TO BE DEVELOPED TO BE COMPETITIVE
- COMMON TEST DATA FOR COMPOSITE SYSTEMS IS IMPORTANT TO ADVANCING THE USE OF COMPOSITES
- GROWTH METHODS ARE NEEDED TO INTEGRATE OTHER SYSTEMS INTO COMPOSITES (I.E. SMART STRUCTURES , DUCTS / WIRES, COATINGS)

Workshop

Closed-Mold Manufacturing of High Performance Composite Missile Structures

15-16 May 1995

Missile System Producers Session

Jerry Lehman
(314) 233-5824

McDonnell Douglas Aerospace

McDonnell Douglas Aerospace - East

GP44-0550-3-V

Related MDA Experience

Low Cost Composite Weapons (LCCW)

- Eglin AFB, AFATL/FXV
- F08635-88-C-0131

Resin Transfer Molding

- GreatLakes Composites Consortium (GLCC)
- TDL 91-07

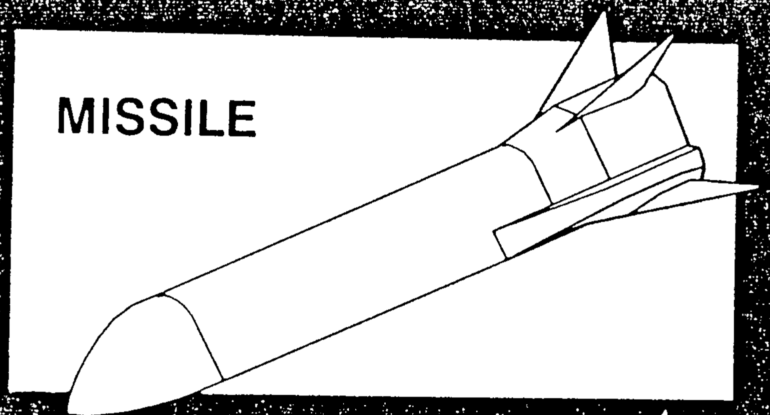
RTM Implementation of F/A-18E/F

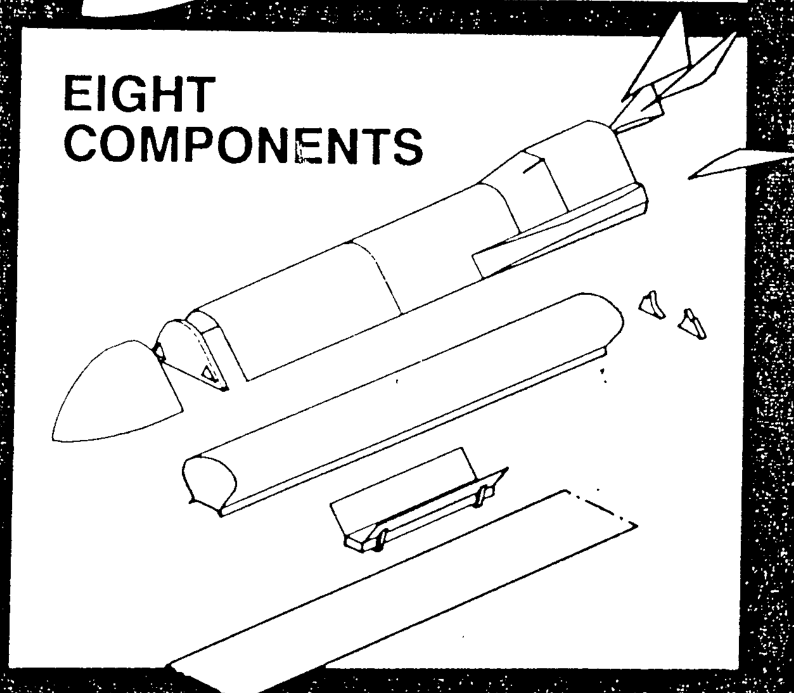
- Outer Wing Leading Edge Seals
- Material and Process Specifications
- Design Allowables

IRAD

LOW COST COMPOSITE WEAPONS (LCCW)

27 FEB 90





PURPOSE

Develop broad technology base in low cost weapon construction

ACTIVITY

Technical evaluation, tooling, fabrication, assembly, testing, production costs, design guidelines

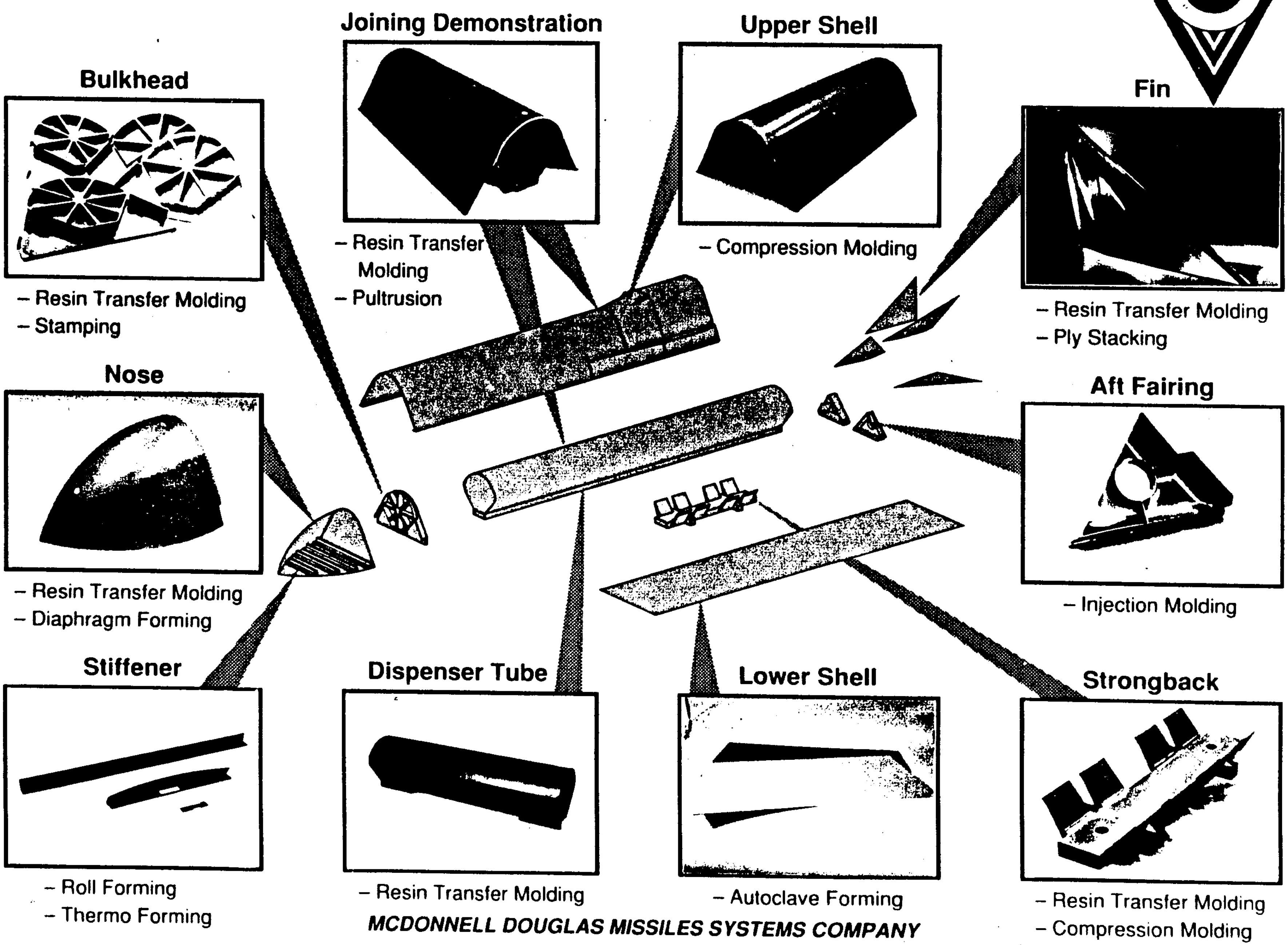
TECHNOLOGIES

- Processes
  - Resin transfer molding
  - Pultrusion
  - Compression molding
  - Diaphragm forming
  - Stamping
  - Roll forming
  - Ply Stacking
  - Injection molding
- Materials
  - Thermoplastics
  - Thermosets
- Assembly approaches
- In-process control

4

UNCLASSIFIED
GP11-0355-1-C/lj

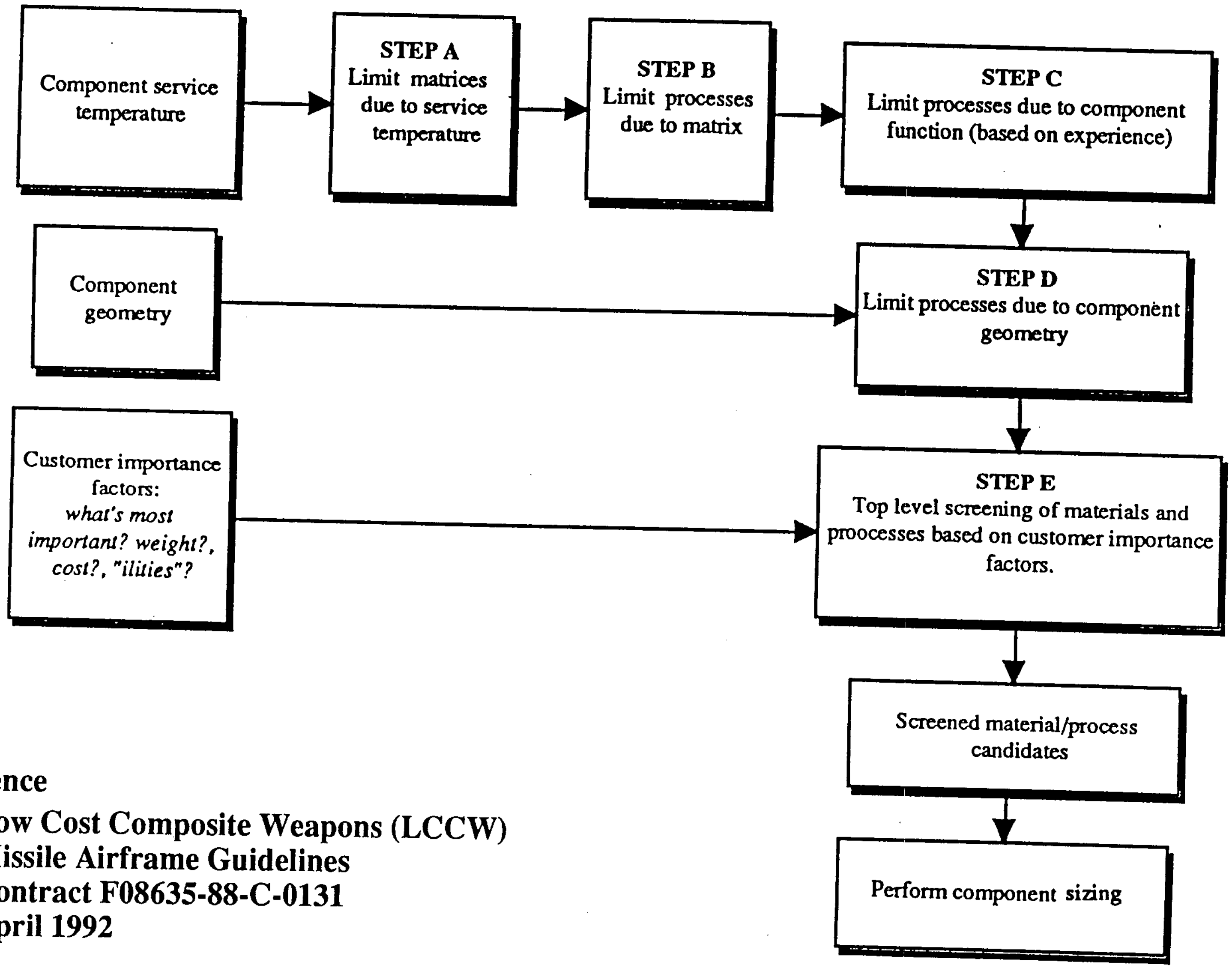
LCCW Components



MCDONNELL DOUGLAS MISSILES SYSTEMS COMPANY

5

Process For Screening Composite Manufacturing Approaches



Reference

Low Cost Composite Weapons (LCCW)
Missile Airframe Guidelines
Contract F08635-88-C-0131
April 1992

STEP A - Limit Candidate Matrix Systems Due to Component Service Temperature

MATRIX	TYPICAL SERVICE TEMPERATURE RANGE (°F)[1]				
	<225	225-350	350-500	500-600	600-800
THERMOSET					
Vinylester	●				
Epoxy		●			
Bismaleimide (BMI)			●		
Polyimide				●	
Polybenzimidazole (PBI)					●
THERMOPLASTIC					
Polyphenylene Sulfide (PPS)	●				
Polyetheretherketone (PEEK)		●			
Polyetherimide (PEI)		●			
Polyarylethersulfone (PAES)		●			

⇨ TYPICALLY INCREASING PART COST

[1] Temperature ranges are typical and will vary dependent on time at temperature, specific matrix system, and matrix mositure absorption.

STEP B - Limit Processes Due to Matrix

MATRIX \ PROCESS	INJECTION MOLDING	PULTRUSION	RESIN TRANSFER MOLDING	COMPRESSION MOLDING Disc.	COMPRESSION MOLDING Cont.	FILAMENT WINDING	STAMPING	THERMO-FORMING	DIAPHRAGM FORMING	VACUUM BAG/ AUTOCLAVE[1]
THERMOSET										
EPOXY		◕	●[2]	●	●	●				●
VINYLESTER (VE)		●[2]		●	◕					
BISMALEIMIDE (BMI)		○	◕	○	◓					●
POLYIMIDE (PI)				◓	◕	◓				◕
POLYBENZIMID-AZOLE (PBI)	◓			○[3]	◓					○
THERMOPLASTIC										
POLYPHENYLENE SULFIDE (PPS)	●[2]	◓			◕	◓	●[2]			◕
POLYETHERETHER-KETONE (PEEK)	●[2]	◓			◕	◓		◓	◕	◕
POLYETHERIMIDE (PEI)	●[2]	◓			◕	◓		◓	◓	◕
POLYARYLETHER-SULFONE (PAES)	◕	○			◕	○		◓	◓	◕

KEY			
● PRODUCTION READY	◕ SCALE-UP REQUIRED	◓ DEVELOPMENT REQUIRED	○ HIGH RISK

Blank boxes in table indicate the matrix is not compatible with process or the material forms are not available for that process

Notes:

1. Consider only thermoset materials.
2. Demonstrated in commercial production applications, will need further development for transition to aerospace application
3. Consider only chopped prepreg not sheet molding compound.

STEP C - Limit Processes Due to Component Function Based On Airframe Composite Design Experience

PROCESS / COMPONENT	INJECTION MOLDING	PULTRUSION	RESIN TRANSFER MOLDING	COMPRESSION MOLDING		FILAMENT WINDING	STAMPING	THERMO-FORMING	DIAPHRAGM FORMING	VACUUM BAG/ AUTOCLAVE [3]
				Disc.	Cont					
RADOME / NOSE	●		●	●	● [2]	●	●	●	●	●
MISSILE BODY [1]		●	●	●	●	●		●	●	●
FRAMES / BULKHEAD			●	●			●			4
STRONGBACK		●	●		●					●
FINS	●		●	●	●		●	●	●	●
NON-STRUCTURAL FAIRINGS	●	●	●	●			●			
ROCKET MOTOR CASE		●	●		●	●				

Notes:

1. The missile body includes the dispenser tube, guidance shell, mid body, warhead shell, interstage structure, and fuel tank.
2. Assume a woven commingled sock is used.
3. Consider only thermoset materials.
4. It is feasible to fabricate a bulkhead using autoclave processing yet it is not optimum due to labor intensity.

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STEP D - Limit Processes Due to Component Geometry (Fin Example)

GEOMETRY/ FEATURES [5]	CANDIDATE FABRICATION PROCESSES								
	INJECTION MOLDING	RESIN TRANSFER MOLDING	COMPRESSION MOLDING			STAMPING	THERMO-FORMING	DIAPHRAGM FORMING	VACUUM BAG/ AUTOCLAVE [1]
			TS Disc.	TS Cont.	TP Cont.				
1-PIECE CO-CURED (NO ASSEMBLY)									
WITH ROOT FITTING & CORE		◐							◐
MULTI-PIECE CONSTRUCTION									
INTEGRALLY RIB STIFFENED WITH BONDED FITTING	● [2]	◐ [3]	◐	◐ [3]	⊖ [2,3]	◐ [2]			● [3]
BONDED CORE & ROOT FITTING	◐ [2]	◐	◐	◐	⊖ [2]	◐ [2]	⊖ [2]	⊖ [2]	●
VARIABLE SKIN THICKNESS	◐	◐ [3]	◐	◐ [3]	⊖ [3]	◐			● [3]
NET MOLDED LEADING & TRAILING EDGES	●	◐ [3]	◐	◐ [3]	⊖ [3,4]	◐			

KEY (see Figure 2-59 for explanation of categories)

● PRODUCTION READY ◐ SCALE-UP REQUIRED ⊖ DEVELOPMENT REQUIRED ○ HIGH RISK

Blank boxes in table indicate process is not capable of fabricating that geometry/feature

Notes:

1. Consider only thermoses materials.
2. Thermoplastic bonding/joining methods are less developed than those for bonding thermosets.
3. Process is more labor intensive due to additional effort required to place stiffener material into mold cavity and/or incorporate ply drop-offs into ply set.
4. Consider using a drapeable thermoplastic material form such as commingled or co-woven fabric.
5. See Figure 2-48 for illustrations of geometry/features.

STEP E - Consider Customer Importance Factors

CHARACTERISTIC[1] \ MATRIX	VINYL ESTER	EPOXY	BMI	PPS	PEI	PAES	PEEK
Cost[2]	●	◕	◔	◒	◷	○	○
Processing Cycle Time[3]	◕	◔	○	●	●	●	●
Cure/Consolidation Temperatures	● *RT-325 °F*	◕ *250-350°F*	◒ *350-450 °F*	◔ *625-650°F*	○ *625-720°F*	○ *650-680°F*	○ *720-750°F*
Equilibrium Moisture Absorption *(.15-2.3% by weight)*	◷	○	○	●	●	●	●
Damage Tolerance	◷	◔	○	◒	●	●	●
Database Availability	◔	●	◒	○	○	○	◔
Solvent Resistance	◒[5]	◒	◒	●	◷	◷	●
Shelf Life	○	○	○	● none	● none	● none	● none
Service Temperature	○	◔	●	○	◒	◒	◷
Processability[4]	●	◒	○	●	◒	○	○

KEY					
●	◕	◒	◔	◷	○
BEST →					*WORST*

Notes:

1. Range values shown in parentheses represent the highest and lowest value for each characteristic. Values are approximate, and may vary.
2. Cost based on unidirectional prepregd tape prices.
3. Processing cycle times depend on the process as well as the matrix material. In general, thermoplastic cycle times are less than thermosets, with the exception of SMC compression molding which has relatively fast cycle times.
4. Processability is compared within thermoplastics and thermosets only, not between thermosets and thermoplastics.
5. Based on Novolac chemistry.

Fiber Cost and Performance Comparisons

CHARACTERISTIC[10] / FIBER	E-GLASS	S2-GLASS®	ARAMID[1]	HIGH STRENGTH CARBON[2]	INTERMEDIATE MODULUS CARBON[3]
Approx. Roving Cost *($1.50/lb - $47.00/lb)*	●	◕	◑	◔	○
Tensile[4] Strength *(500.0 - 740.0 KSI)*	○	◕	◔	◑	●
Compressive[5] Strength *(40.0 - 200 KSI)*	◑	◕	○	◕	●
Tensile Modulus *(10.5 - 40.0 MSI)*	○	◔	◑	◕	●
Specific Fiber Toughness	◑	◕	●	○	○
Dielectric[6] Constant *(4.0 - 6.7)*	◑	◕	● (Lowest)	Conductive	Conductive
Dissipation[6] Factor *(0.001 - 0.014)*	● (Lowest)	◕	◑	Conductive	Conductive
Density *(0.052 - 0.094 lb/in³)*	○	◑	●	◕	◕
Material Compatibility	●	●	●	○[7]	○[7]
UV Stability/ Temperature Resistance	●	●	○[8,9]	●	●

KEY				
●	◕	◑	◔	○
BEST	→			WORST

__Notes:__

1. Kevlar ® 49
2. AS4 12K Carbon
3. IM6 Carbon.
4. Based on fiber properties.
5. Based on undirectional composite properties.
6. Properties measured at 1 MHz, 72°F per ASTM D150.
7. Galvanic corrosion problems occur when carbon materials come into contact with aluminum and some steels.
8. __Some__ studies indicate that when used as a composite, aramid shows no degradation due to UV exposure, because of screening properties of the resin matrix.
9. Long term service limited to less than 400°F.
10. Range values shown in parentheses represent the highest and lowest value for each characteristic. Values are approximate and may vary depending on test conditions, matrix, fiber manufacturer, etc.

12

Cost Versus Process Comparisons

TYPICALLY INCREASING TOTAL PRODUCTION COST →

COST / PROCESS	MATERIAL[3]	EXPENDABLE MATERIAL[8]	LABOR	INITIAL TOOLING[4]
Injection Molding	◕		●	◷
TS Disc Compression Molding	◕		◕	◷
TS Pultrusion	◕		◕	○
Stamping	◑		◕	◷
Resin Transfer Molding[5]	◕ Fiber/Resin ◔-○[6] Preform/Resin		◔ Fiber/Resin ◑ Preform/Resin	◑
Wet Filament Winding	●	●[7] (bagging materials)	◔ - ◷	● - ◑
TS Cont Compression Molding	◑		◷	◑
TS Hand Lay-Up/Autoclave	◑	● (bagging materials)	○	●
TP Pultrusion	○		◕	○
Diaphragm Forming	◷	○ (diaphragms)	◑	◑
TP Cont Compression Molding	○[1]		◷	◔
TP Hand Lay-Up/Autoclave	○[1]	◑ (bagging materials)	○	◕

Notes:

1. TP Cont Compression molding and Hand Lay-up/Autoclave assumes using woven commingled material due to drapeablitiy.
2. Relationships are based on knowledge gained during LCCW and experience of the LCCW team.
3. Relative costs reflect a general trend, and may change based on part configuration and/or production quantity. Also, material costs assume glass reinforcement.
4. Tooling cost becomes negligible for large production quantities, but should be considered for small quantities.
5. Two types of RTM are considered: "Fiber/Resin" which involves laying-up plies of woven or stitched materials and "Preform/Resin" involves using a fiber preform that eliminates ply cutting and lay-up operations but increases material cost.
6. Preform costs can vary significantly depending on the complexity of part geometry.
7. Vacuum bagging is used only if autoclave cure is required.
8. Blank box indicates that no expendable material is required or if required, the cost is minimal.

KEY					
●	◕	◑	◔	◷	○
LOWEST COST	→				HIGHEST COST

13

Summary

- Composite missile parts demonstrated
- Several composite processes to choose from
- Process selection is temperature, geometry and rate dependent
- RTM applies to many missile parts
- RTM advantages
  - Structurally efficient laminates
  - Near net shape parts
  - Potential for combining parts

Institute for Defense Analysis

Industry Government Workshop
Closed Mold Manufacturing of High Performance Polymer Composite Missile Structures

May 15-16, 1995

W. H. Fossey

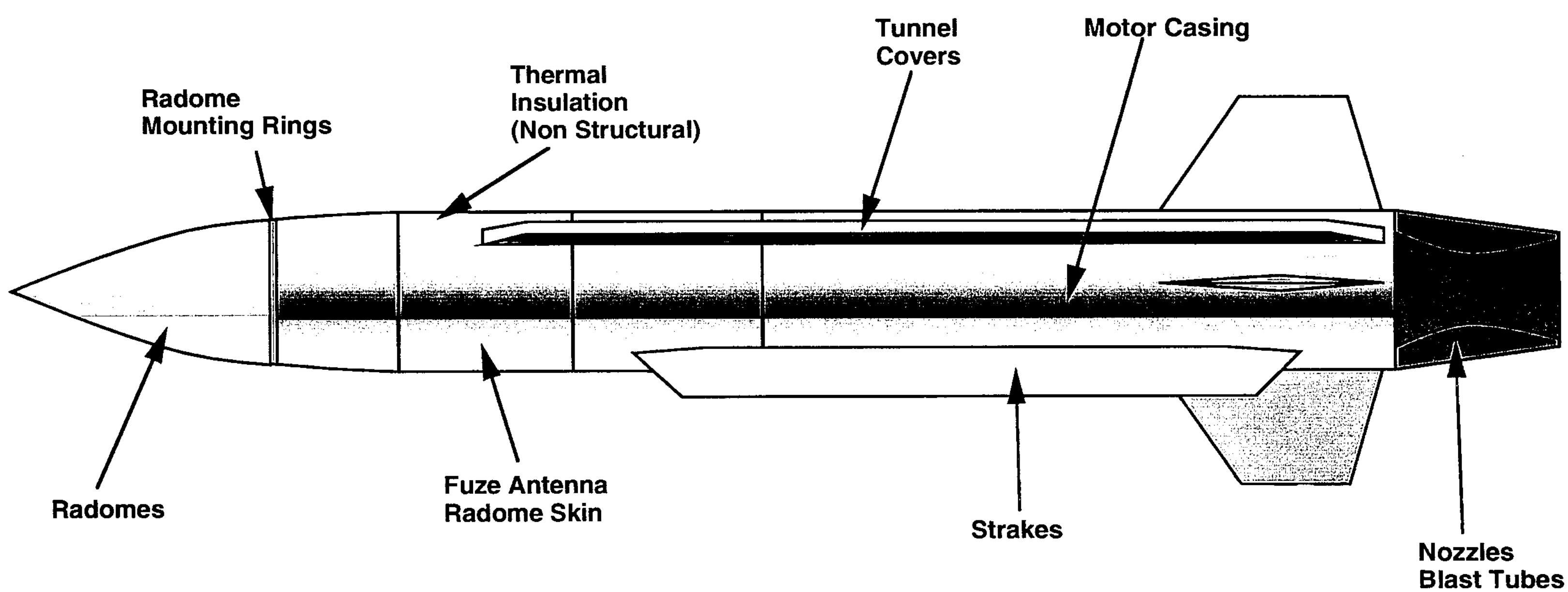
Overview

Current Composite Applications Are Limited

New Program Objectives Open More Applications For Composites But Face:

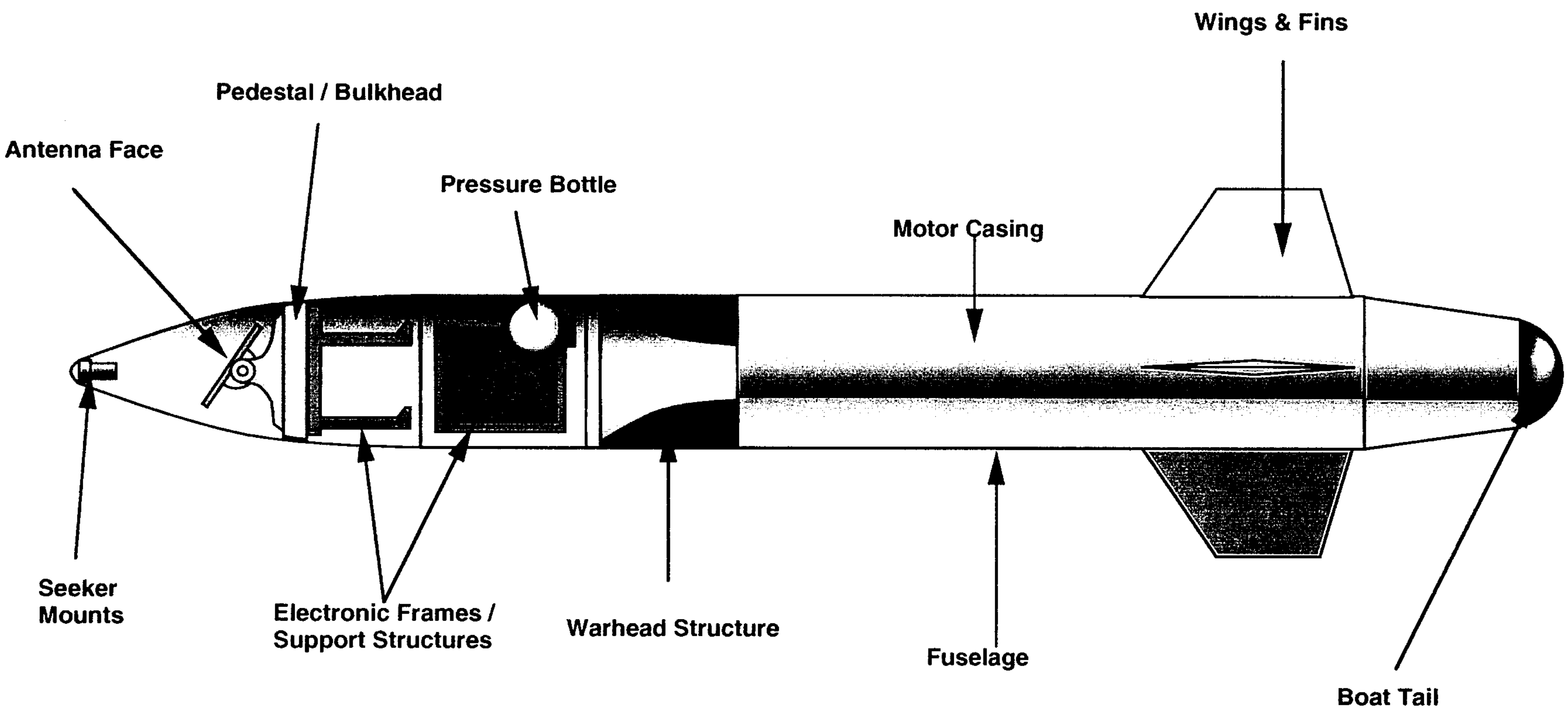
- **Design Communities Unfamiliar with the Materials**
- **A Lack of Missile-specific Design Data**
- **Aggressive Cost & Schedule Goals**

Current Applications of Composites (Combined) Raytheon Missiles



95T-25503

Potential Uses for Composites in Missiles



95T-25504

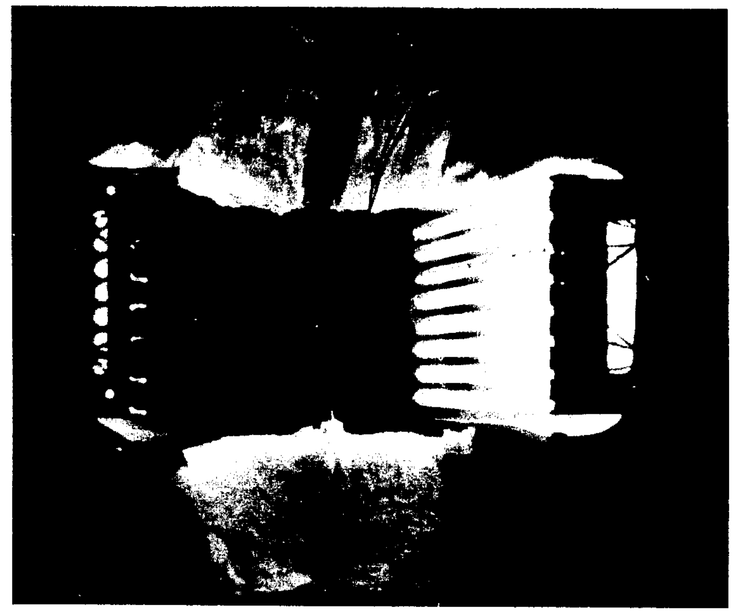
Raytheon Electronic
Systems Division

Raytheon Electronic
Systems Laboratories

Raytheon

Requirements

- Design for Three Environments
  - Storage
  - Captive Carry/Deployment
  - High Speed Flight
- Available Data Bases Do Not Address Flight Regime Well
  - Short Term/High Temperature Data Lacking
  - Large Number of Specialized Conditions
  - High Gradients Through Structure
- Expanded Analyses Required
  - Allowables Loosely Defined



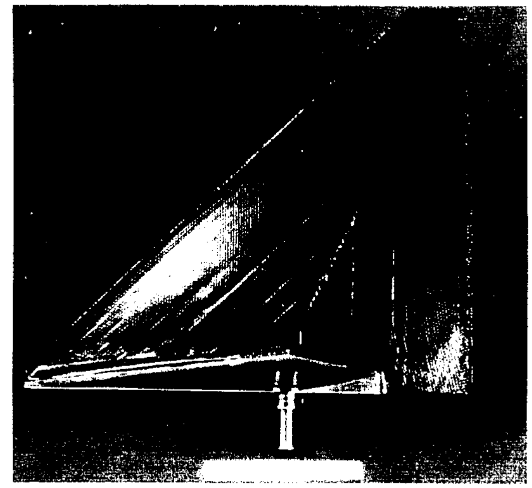
Raytheon Electronic
Systems Division

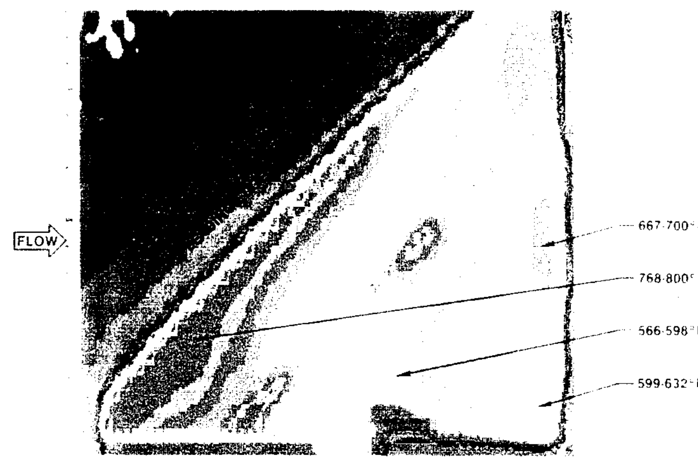
Raytheon Electronic
Systems Laboratories

Raytheon

Requirements (Cont)

- Specialized Qualification Testing Required
  - Elevated Temperature Structural Testing Required
    - Static
    - Dynamic
  - Hot Flow Test Facility
  - Hot Wind Tunnel Testing
- Compatibility with Existing Launch Hardware





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12

Operational Issues

Thermal Management For Internal Electronics

- Short Duration (Flight)
  - Metallic Inserts
  - Heat Spreaders
- Long Duration (Captive Carry/Test)
  - Active Cooling

Attachment

- Localized Bearing Loads
  - High Fatigue Environment

Operational Issues (Con't.)

Mounting Rings, Secondary Inserts

- Weight Penalty
- Expense
- Bondline Temperatures
- Pullout Strength

Operational Issues (Con't.)

Grounding

- Electronics Ground
- EMI/RFI
- Static Charge

Permeability

- Inert Gases
- Water

Operational Issues (Con't.)

Expansion Matching

- Seals
- Stresses in Electronic Substrates

Damage Tolerance

- Factory
- Wear Characteristics
- Field

Production Issues

Design Lead Times

- Small Design Resource Pool
- Process/Design Interaction
- Extensive Analysis
- Multiple Vendors Often Required

Prototype Lead Times

- Tooling
- Materials
- Process Development

Production Issues (Con't.)

Process Control

- Documentation
  - Material & Process Specifications
  - Statistical Process Control
- NDI
  - Requirements
  - Standards Development

Production Issues (Con't.)

Small to Medium Incremental Buys

- Dis-incentive for Effective Development
- Minimum Buy Materials Issues
  - Price
  - Storage
- Limits Tooling from Achieving Full Potential

Plant Environment

- High Assembly/Disassembly Frequency
- Repairability
- Electrostatic Discharge Concerns

Summary

- Significant Challenges Are Presented by New System Needs
  - Reduced Weight
  - Increased Performance
  - Signature Requirements
  - Cost Effectiveness
- Government/User/Supplier Community Needs to Work Closely to Achieve Common Goals
- Systems Designers Recognize the Need to Expand the Application of Composite Materials
- Payoff Will be Higher Performance Affordable Systems

WORKSHOP ON CLOSED-MOLD MANUFACTURING OF HIGH PERFORMANCE COMPOSITE MISSILE STRUCTURES

15 May 1995

Richard Hilscher
Program Manager, Kinetic Energy Weapons

Rockwell Aerospace
Rocketdyne

95KEW-134- 1

OVERVIEW

- Rocketdyne background and composite applications
- Current structural component designs
- Application opportunities
- Challenges and issues

Rockwell Aerospace
Rocketdyne

95KEW-134-2

INTRODUCTION

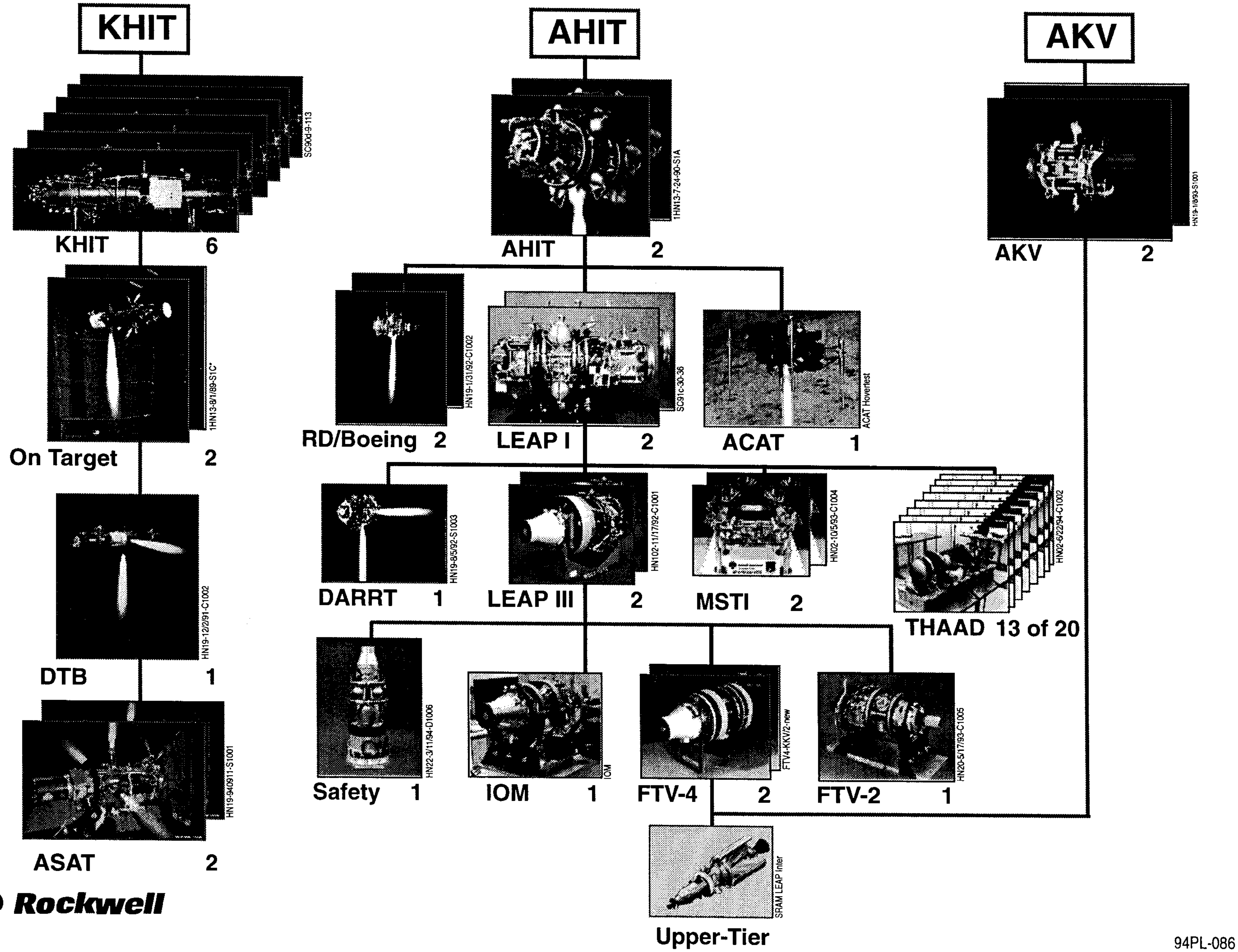
- **All Rockwell KEW kill vehicles and KV propulsion systems have been built by Rocketdyne Division**
- **Current Rocketdyne Kinetic Energy Weapons (KEW) Programs**
  - THAAD
  - ASAT
  - DARRT/LEAP
  - EKV
  - Navy TMD
- **Presenter: Richard Hilscher**
  - THAAD dem/val program manager, 12/91 - 9/94
  - THAAD long range planning, 9/94 - present

KEW STRUCTURE APPLICATIONS/EXPERIENCE

- Rocketdyne has experience with composite missile structures
- Actively investigating composites for current and future programs
- Rocketdyne KV and propulsion system structures history

System	Inner Structure	Outer Shell
SABIR FE	Composite	N/A
KHIT hover vehicle	Machined Al	Composite
AHIT hover vehicle	Composite/Al	N/A
LEAP kill vehicle	Composite/Al & Al/BeAl	N/A
ASAT kill vehicle	Composite/BeAl	N/A
THAAD DACS	Machined Al	Composite (LMSC)
THAAD DACS Technology	Composite	N/A
EKV Kill Vehicle	Composite/Al	N/A

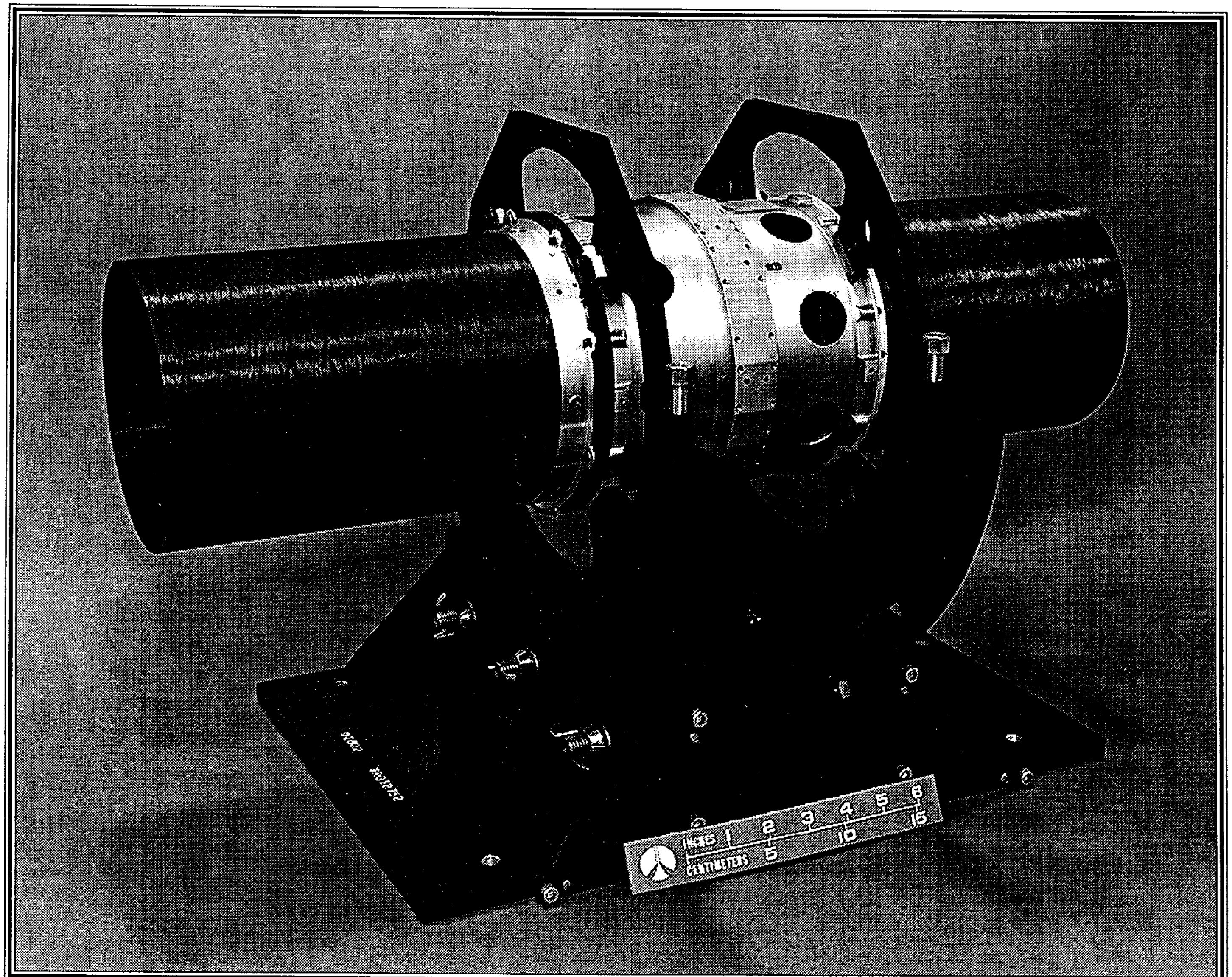
KV CONFIGURATION/BUILD LINEAGE



Rockwell

94PL-086

LEAP STRUCTURE



1HN91-2/7/90-D1B*

Rockwell

95PL-059

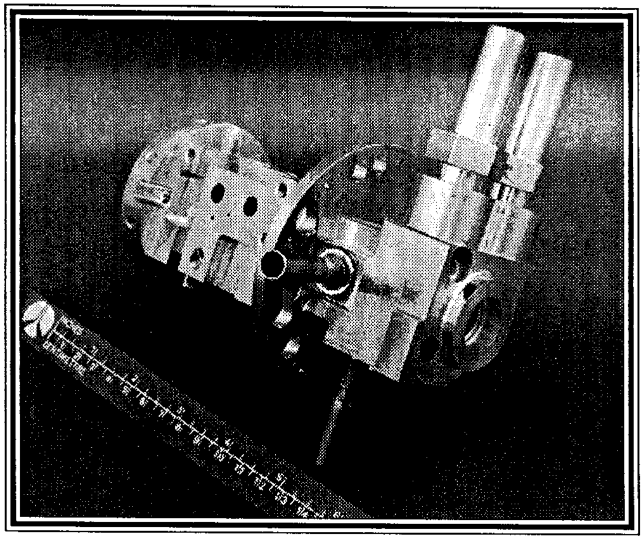
REASONS FOR LIMITED USE

- **Rocketdyne experience base is primarily with machined aluminum and BeAl**
  - KEW - composite experience - straight cylinder
- **Technical concerns related to composites**
  - Heat transfer key
  - Integrated mounting flanges
  - Materials compatibility
  - Long term storage
  - Tolerances
  - Testing
- **Composite advantage not a system driver**
- **Incorporation of composites for production requires some pathfinder activity and cost**

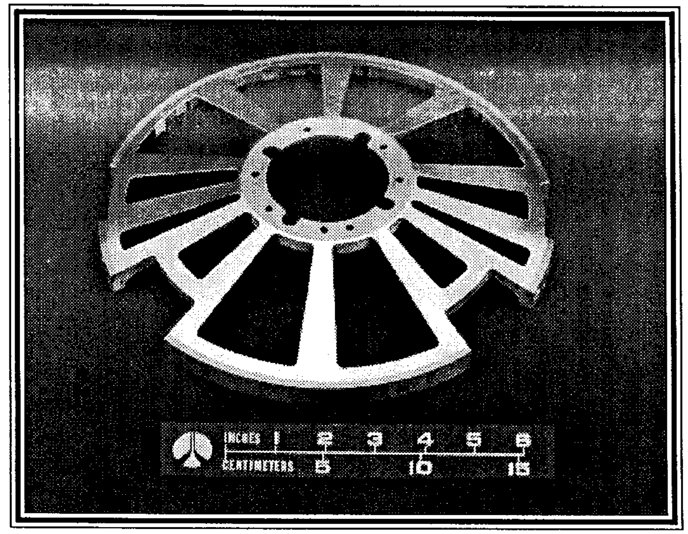
RECENT KV STRUCTURAL COMPONENTS

- **THAAD DACS and EKV bulkheads**
  - Light weight/high strength components
  - Challenging tolerances
  - Complex geometry
- **EKV primary and separation system structure**
  - Light weight/high stiffness
  - Integrated booster attachment
  - Truss-like geometry
- **THAAD DACS divert and ACS manifolds**
  - Dual purpose structural member/manifold
  - Complex internal passages
  - Complex external geometry

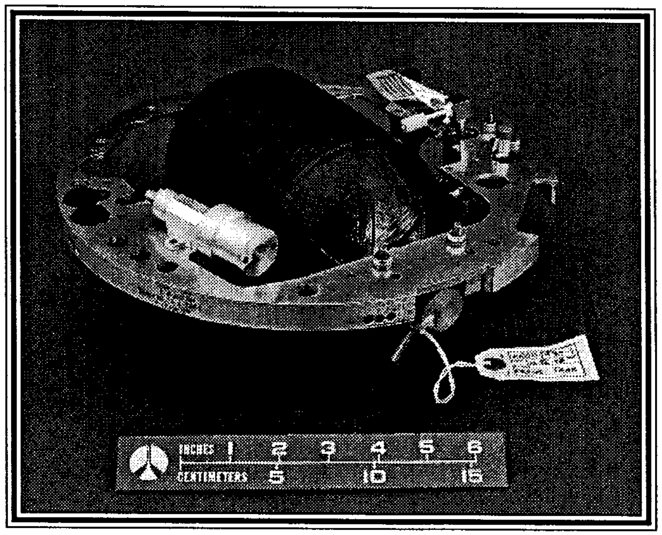
DACS MAJOR STRUCTURAL COMPONENTS



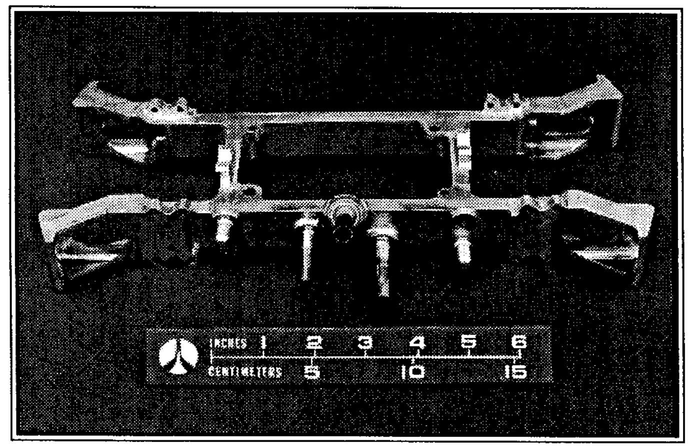
Divert Manifold



Divert Bulkhead



Pressurant Bulkhead



ACS Manifold

Rockwell

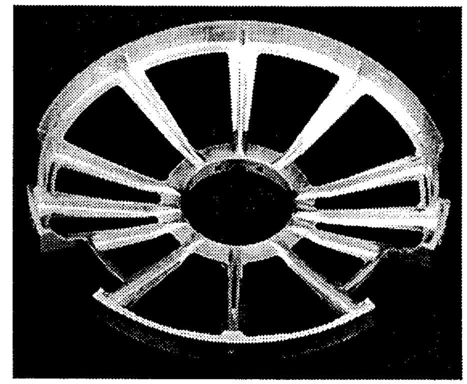
94PL-078

PRODUCIBLE COMPOSITE STRUCTURE BULKHEADS FOR THAAD KKV DACS PROPULSION

Program Description

- Identify DACS bulkheads which are candidates for lightweight, more producible composites fabrication technology (four identified)
- Design and fabricate prototype composite test articles
- Conduct ground tests to simulate worst case environments
- Perform manufacturing analysis to evaluate key issues and projected production costs

THAAD Aft Divert Bulkhead



Requirements

- Reduce weight by 20-50% compared to baseline aluminum designs
- Match or exceed stiffness and strength compared to aluminum
- Satisfy dimensional tolerance requirements
- Reduced per unit production cost compared to aluminum
- Satisfy design envelope
- Resistant to liquid propellant (ACS Manifold)
- Elevated temperature capability
- Damping (reduce shock load transmission)

Program Plans

Funding	FY '94	FY '95	FY '96
	$200K	$600K	$600K

Schedule

Structure fab demo - FY '94 - '95

Ground test demo - FY '95 - '96

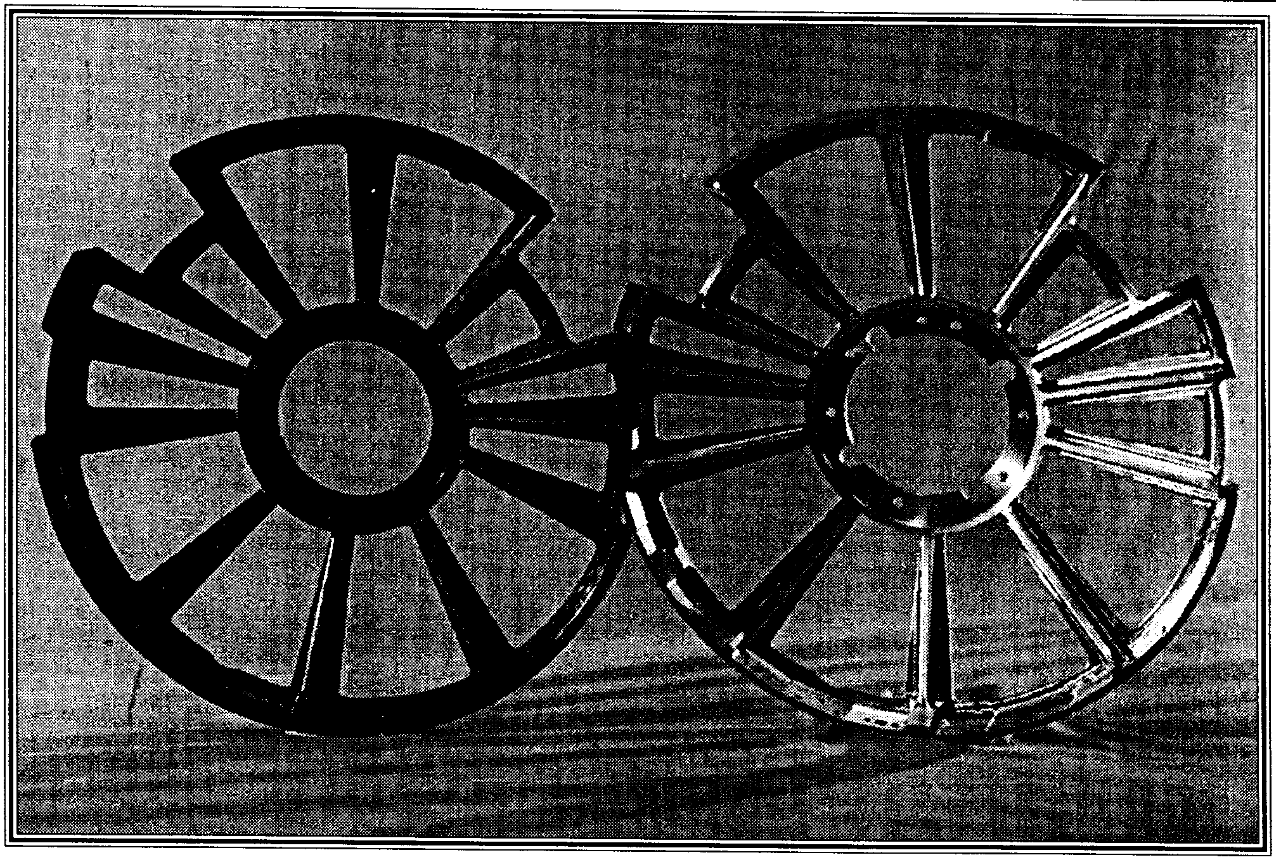
Flight test demo - FY '96 - '97

Rockwell Aerospace
Rocketdyne

95KEW-134-14

THAAD COMPOSITE AFT DIVERT BULKHEAD

SPARTA



- Baseline design machined 7075-T73 aluminum
- Near net shape matched metal net molded composite
- Composite ≈ 1/2 production cost of aluminum
- IM7 composite exceeds strength and stiffness requirements
- Composite has >30% weight savings compared to aluminum

Rockwell

95PL-057

KEW TESTING AND ANALYSIS REQUIREMENTS

- **Material level data**
  - Supplier coupon test data
  - Material property data
- **Component level tests**
  - Environmental
  - Critical loading
  - Modal
  - Non-destructive
  - Destructive
  - Combination (loading with environment)
- **System level test**
  - Static hotfire
  - Hover
  - Separation
  - Flight

COMPOSITE MATERIAL INITIAL EVALUATION

- **General material property information**
  - Tensile, compressive, bending strengths
  - In-plane, inter-laminar, lap shear strengths
  - Stiffness
  - Fatigue
- **Environmental effects (program specific)**
  - Temperature (-46°C to + 177°C)
  - Humidity (5% - 75%)
  - Vacuum (12kPa - 106kPa)
- **Data obtained through prior supplier/contractor experience and/or specifically designed coupon test program**
  - Rocketdyne ME&T, Structures to evaluate existing data
    - Evaluate raw data to determine quality, applicability
    - Reliability (i.e. A, B basis) based on program specific requirements
    - Determine additional required data
  - Utilize supplier expertise
    - Supplier most likely to perform testing
    - Rocketdyne intimately involved (on-site) during testing

COMPOSITE MATERIAL PART-SPECIFIC EVALUATION

- **Sub element testing**
  - Test specimens simulating critical areas, approximate lay-ups
    - Specific geometries (T-sections, I-sections)
    - Fillets
    - Fastener locations
  - Critical loading, environment
    - Vibration, shock
  - Inspect for undesirable post-test conditions (delamination, cracking, voids)
    - Ultrasonic
    - X- ray
    - Dissection

Rockwell Aerospace
Rocketdyne

95KEW-134-12

APPLICATIONS OPPORTUNITIES FOR CLOSED-MOLD COMPOSITES

- **Current**
  - Bulkheads
  - Aeroshell
  - Primary structure (Exo)
  - Secondary structure
- **Future ?**
  - Structural manifolds
  - Thrust chambers

TECHNICAL CHALLENGES FOR CLOSED-MOLD COMPOSITES

- **Tolerances**
  - .025 mm pin hole/true position
  - .025 mm flatness
- **Geometric complexity**
  - 300 + dimensions per part
- **Shock and virbration performance**
  - 0.04g2Hz from 20 -2000 Hz
  - 10 Hz/40g to 5000 Hz/10000g
- **Thermal environments**
  - (-46°C to +177°C)
  - Heat sink capacity
  - Thermal expansion
- **Assembly processes**
  - Welding process replacement
- **Life cycle and long term storage**
  - 20 year year shelf life
  - Fatigue
  - Out gassing
- **Propellant compatibility (manifolds)**
  - Hypergolic propellant loading before delivery
  - MMH/NTO

Rockwell Aerospace
Rocketdyne

95KEW-134-19

ANTICIPATED QUANTITIES

	0 - 5 years	6 - 10 years	Lot sizes
Bulkheads	250	3000	20 - 300
Manifolds	150	2000	20 - 300

SUMMARY

- **More data is required to clearly evaluate composites vs machined/cast/forged metal structure**
- **Pathfinder costs for composites are significant**
  - Design data base development
  - Manufacturing process integration
  - Technical issue resolution
  - User familiarity and confidence
- **Key unknowns**
  - Can closed-mold composite cost be competitive with cast metal plus finish machining?
  - Can composites meet tolerances cost effectively?

Rockwell Aerospace
Rocketdyne

95KEW-134-20

APPENDIX D

MULTI-DIRECTIONAL REINFORCED PREFORMS

WORKSHOP ON CLOSED-MOLD MANUFACTURING OF
HIGH PERFORMANCE COMPOSITE MISSILE STRUCTURES

FIBER MATERIALS, INC.

MULTI-DIRECTIONAL REINFORCED PREFORMS

May 15, 1995
at
INSTITUTE FOR DEFENSE ANALYSES

Presented By:

FIBER MATERIALS, INC.

BIDDEFORD, MAINE

MULTI-DIRECTIONAL REINFORCED PREFORMS

FIBER MATERIALS, INC.

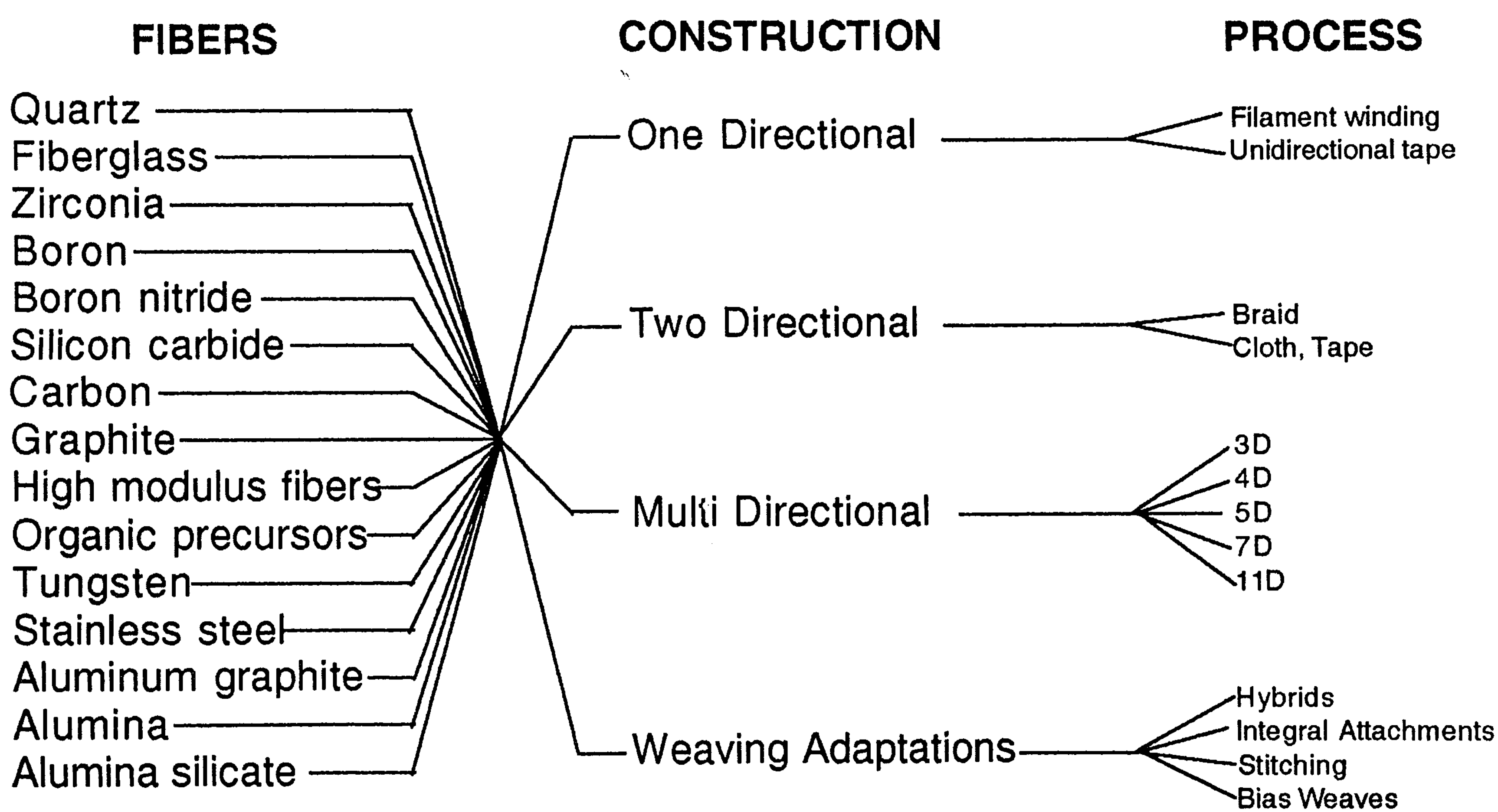
FMI is involved in the research, fabrication, testing and evaluation of advanced composite materials. Specialty weaving capabilities and unique multi-directional or *N-D* fabrication methods represent key strong points related to preform manufacturing.

TOPICS:

- Background of N-D Weave Constructions
- Weave Design Aspects
- N-D Weaves for Closed Mold Manufacturing
  - Weaving Approaches
  - Reinforcement Options
- Quality Control Methods
- Issues/Concerns

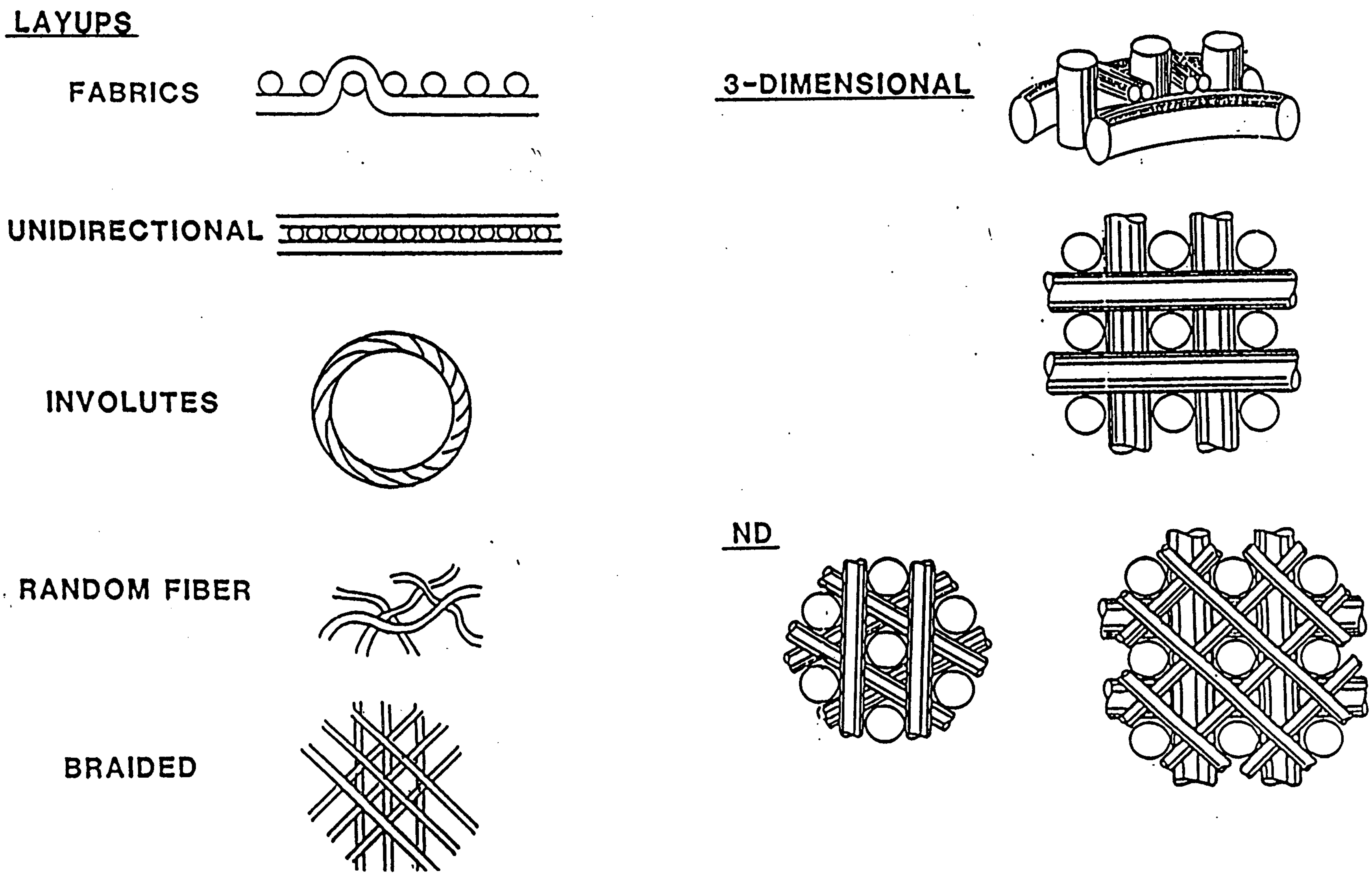
FIBER AND WEAVE ARCHITECTURE OPTIONS

FIBER MATERIALS, INC.



EXAMPLES OF WEAVE CONSTRUCTIONS

FIBER MATERIALS, INC.



MANUFACTURING CAPABILITIES FOR N-D WEAVES

FIBER MATERIALS, INC.

WEAVING PROCESSES RESULT IN A VARIETY OF PREFORM CONFIGURATIONS

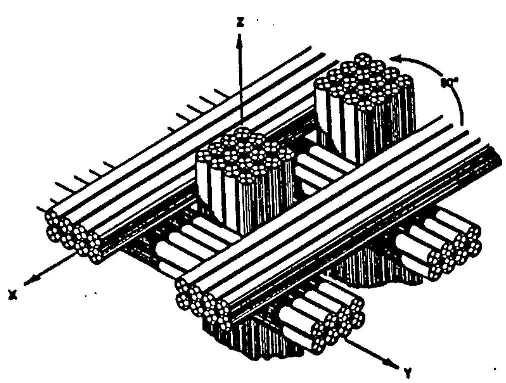
	Characteristic
• Dimensions	0.25 in. ID to 85 in.OD x 60 in. Height
• Thickness	0.15 in. to ~ 10 in.
• Reinforcement Architecture	Tailored Weave Characteristics by Location and Direction
• Shape	Block, Panel, Cylinder, Cone, Ogive, Flanges, or Contoured Shapes using Weave Tooling and Mandrels

DESIGN PARAMETERS FOR N-D WEAVES

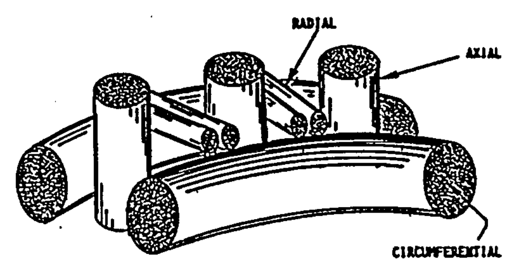
FIBER MATERIALS, INC.

LOCATION, SIZE AND DIRECTION OF YARN BUNDLES DEFINE CONSTRUCTION DETAILS

	Characteristic
• Yarn Spacing (Bundle-to-Bundle, LPI)	0.015 in. to > 0.125 in.
• Volume Fraction (each direction)	5-10% min. to ~ 70% maximum
• Overall Fiber Volume (as woven)	< 35% to 55%
• Fiber Type	Cross Sec. Area, Density, Linear Yield
• Reinforcement Orientation	Standard - 3D, 4D, Etc.
	Hybrid - 2D/3D, 3D/5D



3D ORTHOGONAL WEAVE



3D CYLINDRICAL WEAVE

N-D WEAVE ARCHITECTURE ATTRIBUTES

FIBER MATERIALS, INC.

ADAPTABLE WEAVING PROCESS

- Excellent Design Flexibility

    Directional Fiber Loading
    Hybrid Fiber Capability
    Graded Structures

- Applicable to Automation
- Near Net Shape Configuration

TAILORABLE COMPOSITE PROPERTIES THROUGH FIBER FRACTION LOADING

- Mechanical Characteristics
- Thermal Characteristics
- Ablative Performance
- Mechanical Wear

N-D WEAVES FOR CLOSED MOLD MFG.

FIBER MATERIALS, INC.

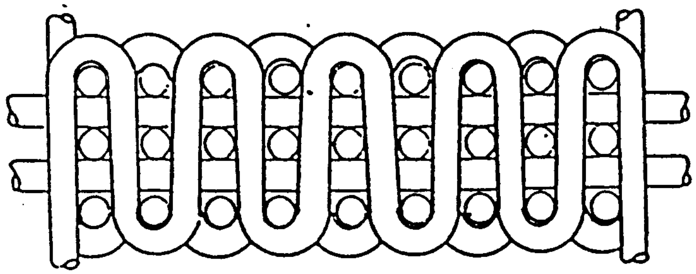
MANUFACTURING APPROACHES

• Weaving Processes-	Modified Textile Loom Manual Loom Stitching Machine
• Woven Product-	Thick Broadcloth Fabric or Narrow Tape Net-Shape Body of Revolution
• Construction Feature-	Collapsible Weave Compressible Weave Tailored Void Paths

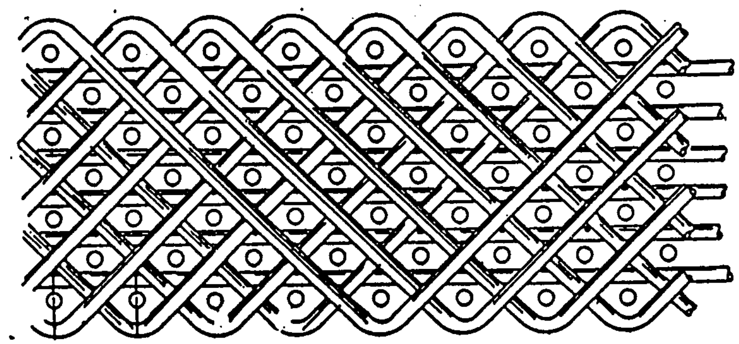
N-D WEAVES FOR CLOSED MOLD MFG.

FIBER MATERIALS, INC.

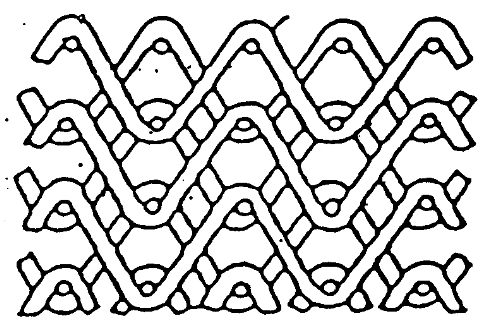
WEAVE CONSTRUCTION POSSIBILITIES



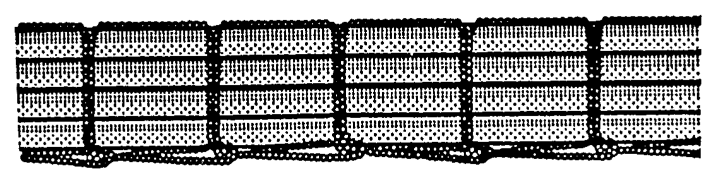
3D ORTHOGONAL



WARP INTERLOCK



ANGLE INTERLOCK



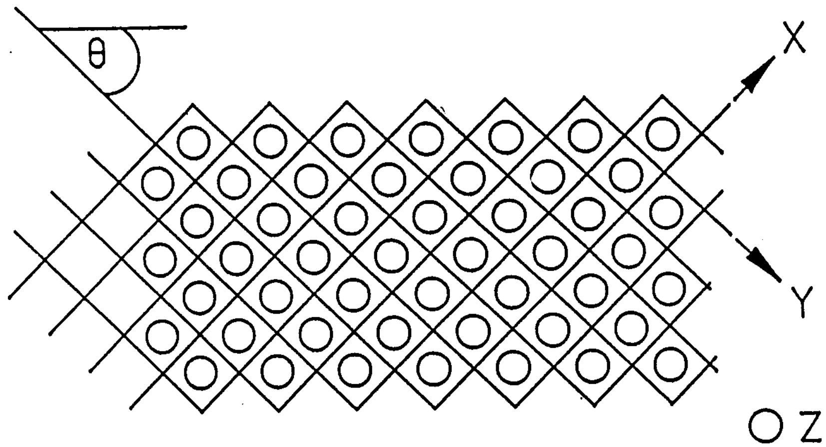
STITCHED

N-D WEAVE FOR CLOSED MOLD MFG.

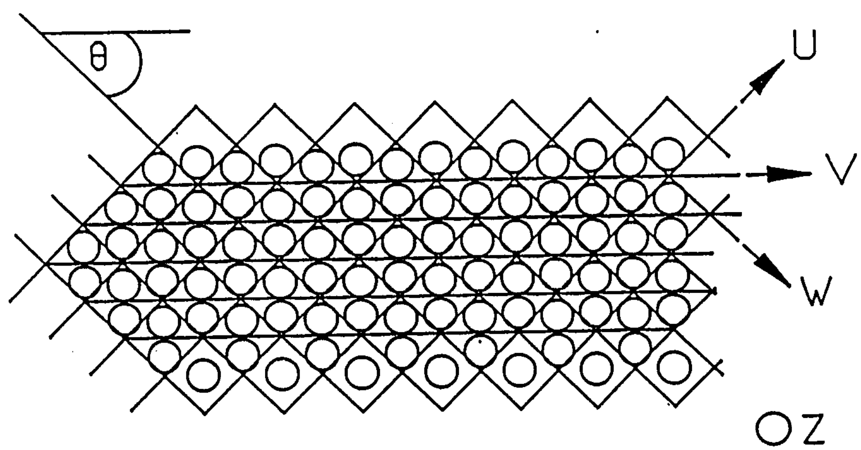
FIBER MATERIALS, INC.

DETAILS OF WEAVE CONFIGURATION

3D BIAS



4D NON-ORTHOGONAL



θ is 45° to 120°

Z Reinforcement is Fill Yarn for Loom Mfg.

QUALITY CONTROLS METHODS

FIBER MATERIALS, INC.

INSPECTION IS INVOLVED THROUGHOUT THE N-D WEAVING PROCESS

• Receiving Inspection	Yarn Certification
	Weave Tooling
• In Process Inspection	Loom Set-Up
	Visual Inspection Every Layer,Row, Etc.
	Shop Floor Paperwork (R&D Traveler,SOP, IPOS)
• Final Inspection	Physical Measurements
	Bulk Density
	X-Ray Radiography

ISSUES/CONCERNS

FIBER MATERIALS, INC.

N-D WEAVING IS A DEMONSTRATED PROCESS; HOWEVER, APPLICABILITY OF THIS CONSTRUCTION TO MOLDED STRUCTURES HAS NOT BEEN EFFECTIVELY EXPLORED.

- To date, N-D weave constructions demonstrated only as coupons and sub-scale components.
- Limited property data exists for N-D weaves
- Effects of molding operation on weave reinforcements not characterized

3M Fluorene Epoxies Opened the Door for Aerospace Grade RTM

JERRY SUNDSRUD
612-733-7221

3M

Outline

1. RTM now meets aerospace requirements
2. Aerospace acceptance of Fluorene Epoxy
3. Other inherent benefits of fluorene epoxy
4. Resin cost relationship to part cost
5. Miscellaneous

3M

RTM Now Meets Aerospace Requirements

Past Issue	Solution
QA of real time resin mixing considered to be unreliable	Offer stable, one-part, premixed and Q.C. tested resin
Lack of high performance resins	New chemistry developed primary structure capable
Lack of working knowledge	Experience and hands on technical service from suppliers
Limited database	1200 mechanical test data points to date, and 1700 more by September, 1995 on PR 500

3M

3M PR 500 Resin

- A one part RTM resin system
- Excellent room temperature stability
- Low viscosity (35-60 CPS) at recommended mold temperature
- Low shrinkage during cure
- Low exotherm during cure
- Completely cured in two hours at 360°F
- Low moisture absorption after cure
- Inherently tough
- High moldulus
- High mechanical properties
- High toughness - CAI over 40 ksi
- Hot/wet performance over 300°F

General Advantages of One-Part Systems

- No Mess of Mixing
- Less Worker Exposure to Chemicals
- No Mix Ratio Concerns
  - Ratio Assured by Supplier
  - QC Testing Completed by Supplier

Additional Advantages Using 3M PR 500 One-Part Resin System

No Transferring of Resin

- Pump Directly from Shipping Containers

No Degassing Necessary

Reduced Heat Exposure of Resin

No Pot Life Concerns

No Pump and Hose Clean Up

- No Solvents Required

PR 500 Database

- Over 2,300 mechanical specimens tested (Design Properties)
- Largest existing database on epoxy RTM resin
- RTM Industry Leader
- Fully characterized in aircraft fluids/ solvents
- Limited fatigue data

Other Inherent Benefits of Fluorene Epoxy

Features	Benefits
• Low Toxicity	• Worker Safety
• Latent Cure System	• Environmentally Friendly - Minimal cleanup
• Flame Retardancy	• No sacrificial material required to pass FAA flame retardancy requirements for primary structure
• Other product forms available with the same chemistry	• Prepreg and other product forms for local reinforcement

3M

Aerospace Acceptance of Fluorene Epoxy

- 9 Applications in production and flying
- Over 200 parts in development for production
- Currently qualified to 11 customer specifications and more in process.
- OEM approved PCD's in place and ISO 9002 approved manufacturing plant
- Navy funded PR 500 processing study in progress

3M

NEWS

Boeing employe

OL. 52, No. 12

D-22

elivery of 777: 777 days and co

by Barbara Murphy
g Commercial Airplane Group
777 Division

he number "7" can be con-

Euralair, Thai Airways International, British Airways, Lauda Air, Japan Airlines, Cathay Pacific Airways and Emirates.

Alan Mulally, 777 Division vice president and general manager at

"We wanted the airplane to have features that the airlines believe add value to their business plan," Mulally said. "That's what has driven our 777 program.

mance. The second is our design/build teams — getting the quality knowledge built into the airplane. Third is our digital product definition — the ability for everyone to

cesses
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Aerospace Acceptance of Fluorene Epoxy

Aircraft Flying PR 500 Today:

Boeing 777

Douglas MD 90

ATR 72

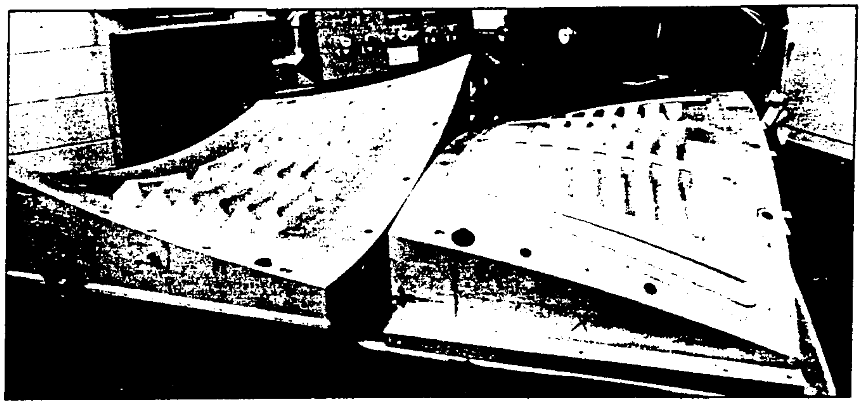
Westland Sea King Helicopter

Sikorsky S61 and HH3 Helicopters

POLYMERS/CERAMICS

Composite RTM component combines 60 parts into one

A resin-transfer-molded (RTM) epoxy composite component manufactured by the Composite Structures Div. (CSD) of Alcoa Composites, Monrovia, Calif., has replaced a 60-piece aluminum assembly in the APU (auxiliary power unit) vent louver for the McDonnell Douglas MD-80 and MD-90 aircraft. The RTM part is also said to eliminate most fasteners, reduce weight from 3.2 kg (7 lb) to less than 1.6 kg (3.5 lb), and cut maintenance costs by 50%. The vent louver is the first commercial-airplane RTM application at Douglas.



A RTM composite vent louver for the McDonnell Douglas MD-80 and MD-90 consolidated 60 parts into one, eliminated most fasteners, and reduced weight by 50% compared with the aluminum assembly it replaced.

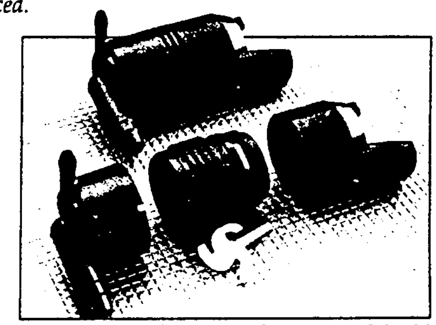
According to CSD, the part was engineered for RTM technology using a one-part epoxy from 3M Co., St. Paul, Minn., reinforced with 50% continuous-filament fiberglass. The PR-500 epoxy can withstand temperatures to 175°C (350°F), which is critical since the louvers are located just aft of the engines, and can experience temperatures up to 105°C (225°F). A one-part epoxy was important to winning acceptance from the Federal Aviation Administration, because it is considered more reliable than two-part materials, which must be mixed in the correct ratios.

For more information: Mike Therson, Composite Structures Div., Alcoa Composites, 801 Royal Oaks Drive, Monrovia, CA 91016; tel: 206/453-6330; fax: 206/453-6327.

Circle 134

Acetal replaces steel, cuts cost of motor housing

Steel has been replaced with Celcon acetal copolymer (Advanced Materials Group, Hoechst Celanese, Chatham, N.J.) in the motor housing of a windshield washer pump manufactured by Delco Products Div., General Motors Corp., Dayton, Ohio, reportedly reducing weight by 13% and cutting manufacturing costs. In addition, the motor housing was consolidated with the terminal and pump housings, allowing production of the three parts as a single all-plastic unit. According to Hoechst, the plastic material enables elimination of secondary manufacturing steps such as stamping, curling, and welding, which were required on the metal housing. Additional savings were made by extending the parts consolidation to a line of five different pumps, standardizing the line into one pump that reduced 35 parts to seven in a single snap-fit unit.



The manufacturer of this windshield washer pump was able to reduce weight, consolidate parts, and cut costs by replacing the steel housing with one made of Celcon acetal copolymer from Hoechst Celanese.

Key to the design is the reported dimensional stability of Celcon acetal TX90, which ensures tight, snap-fit seals to prevent leakage at temperatures ranging from -40 to 110°C (-40 to 230°F). Tests showed that after 1000 hours at room temperature, Celcon had a creep modulus of 1860 MPa (270 ksi), compared with 570 MPa (83 ksi) for nylon 6/6, 475 MPa (69 ksi) for modified nylon, and 1100 MPa (160 ksi) for polyester.

The pump's impeller is made of glass-coupled Celcon GC25A acetal, which is said to have twice the stiffness of the monolithic material. According to Hoechst, the fiberglass is actually bonded to the acetal, rather than simply coated with it. The higher strength that results allows the impeller blades to maintain dimensional stability under the stresses imposed by service at 15,000 rpm, and at the elevated temperatures that could result from operation after the washer fluid is depleted.

For more information: Hoechst Celanese Information Center, 114 Mayfield Ave., Edison, NJ 08818; tel: 800/235-2637. **Circle 135**

Carbon/teflon composite resists creep, chemicals

A Teflon (PTFE) matrix reinforced with high-aspect-ratio carbon fibers has been developed by DuPont Composites, Newark, Del., for applications requiring excellent chemical resistance, no compressive creep, dimensional stability across a wide temperature range, a high degree of toughness, and good wear characteristics. Called Zymaxx, the composite was developed for applications in the processing of glass, petroleum, and chemicals. It is also suitable for fluid power engineering and thermal management equipment.

According to DuPont, Zymaxx delivers longer part life in valve seats and seals; it reduces operating costs in pump and compressor components; and it increases reliability and productivity in gaskets. The material is available in stock shapes as well as parts machined to customer specifications.

For more information: Wayne Gentile, applications manager, Corrosive Environments, DuPont Composites, P.O. Box 6101, Newark DE 19714; tel: 302/451-3177; fax: 302/451-4932. **Circle 136**

at 15% N_2. The exhaust gas temperature reached a maximum of 528C on the relatively hot day. During start of the right engine, we received an indication that the automatic abort systems had activated and that automatic clearing of the engine was taking place. A mechanic found the 10th stage bleed air valve was sticking open and corrected the fault by tapping it. The second right engine start was uneventful.

Moss entered the flight plan into the aircraft's dual flight management system through the multipurpose control display unit on his side. Douglas has made changes to the FMS by adding in-flight monitoring and an increased data base. At the same time, he programmed the FMS to automatically cut back the engine power ratio from a setting of 1.48 to 1.26 at 800 ft. The automatic power reduction feature can be used at noise sensitive airports.

I TAXIED THE MD-90 to Runway 21 at Roswell. Aside from the occasional Air Force F-111 doing touch and goes at the airport, there was little traffic. The rudder pedals steered the aircraft more than adequately for most turns on the ground, and the tiller was only used for sharp turns on

was brisk. A slow rotation to a 20 deg. nose-up attitude started 31 sec. after brake release, and initial rate of climb was 3,500 ft./min. after the landing gear and flaps were retracted. Moss noted the automatic cut back feature had deactivated during the takeoff roll, and he manually reduced power at 800 ft., lowering the climb rate to 2,500 ft./min.

Delta Air Lines' pilots will be able to select thrust levels of 28,000 lb. or 25,000 lb. for each IAE engine on takeoff. Delta has firm orders for 31 MD-90s.

The system worked as advertised on a later takeoff. There are multiple means of disarming the cutback system, including throttle movement after takeoff and sensor data loss. The system automatically disarms and advances power to the go-around level if it detects an engine failure, wind shear or negative climb rate.

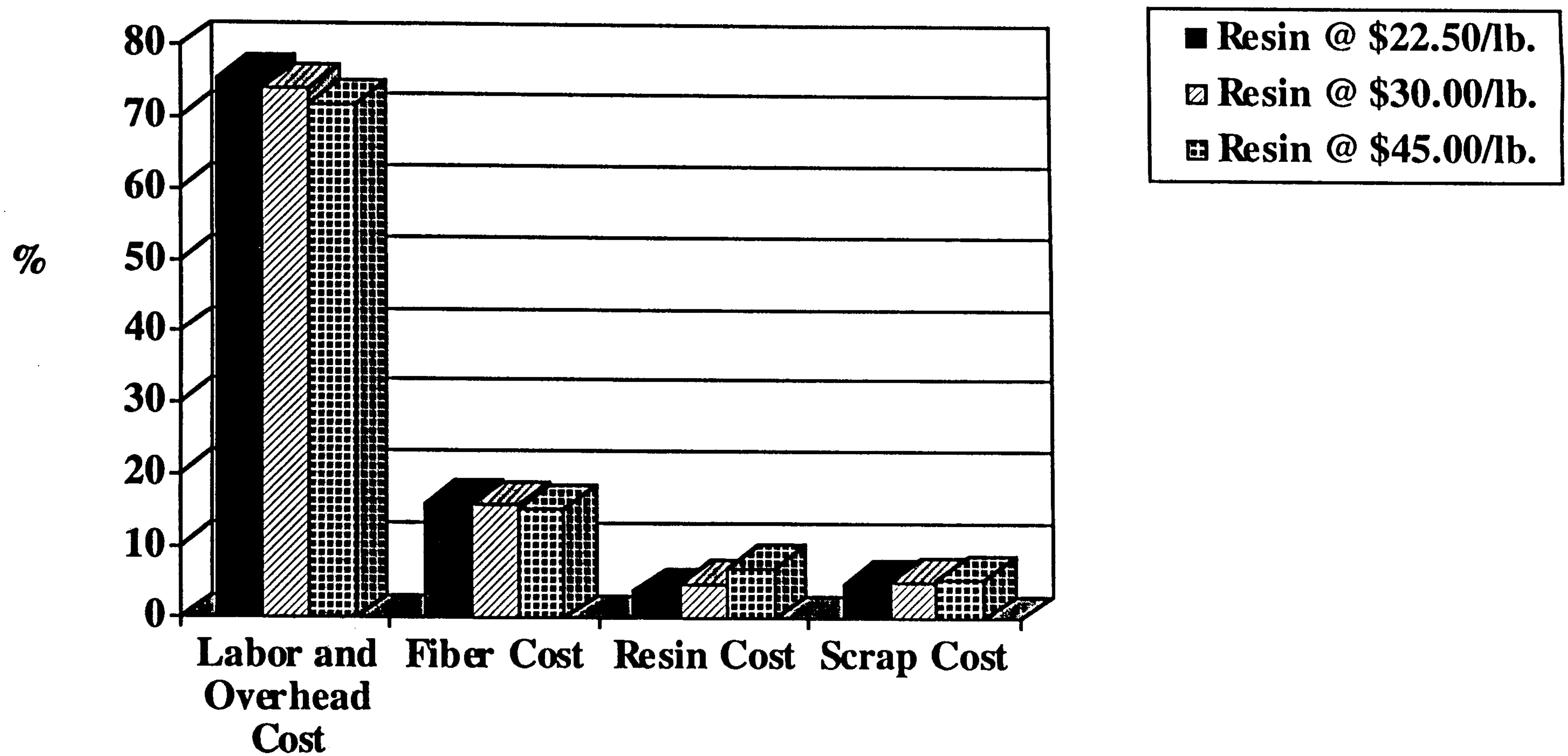
THE MD-90 REACHED an altitude of 10,000 ft. 4 min. after takeoff. Air traffic control held us at that altitude for about 5 min. The autopilot and autothrottle were used for the climbout to 31,000 ft. The workload required to use the MD-90's au-

cluded the 5 min. spent at 10,000 ft. Fuel flow just prior to level off was 4,370 lb./hr./engine, and the total fuel burn from engine start was 4,000 lb. The flight management system (FMS) indicated that 35,600 ft. would be the optimum altitude for our near 123,000-lb. gross weight.

The speed of Mach 0.754 used to reach 31,000 ft. was close to that identified by Moss as the long-range cruise speed for the MD-90. The outside temperature was -33C (-27F) or 13C (6F) above normal at the cruising altitude. Fuel flow at Mach 0.744 was 2,930 lb./hr./engine. The FMS indicated the maximum range speed was Mach 0.694. At that speed, the fuel flow was 2,550 lb./hr./engine. For a maximum speed cruise, Mach 0.793 was used. The fuel flow was 3,220 lb./hr./engine, and the true airspeed was 478 kt. Both Moss and Graves said fuel consumption figures for the MD-90 were generally 15% lower than those of the MD-80.

Another issue resolved in the MD-90 is the effect of fuel cold soaking on the wing. A return to tank fuel heating system has reduced cold soaking and eliminated the need for a separate fuel heating system.

Contribution to RTM Part Cost



RTM Resin Cost Relationship to Part Cost

Test Case: Existing RTM Composite Part Costs = $200/lb.* when Resin Cost = $45/lb.
Resin Content = 32% (Fiber Volume = 60%)

Resin Selling Price	Total Part Cost	A Resin Cost Contribution	B Fiber Cost Contribution @ $45/lb.	C Scrap Contribution 25% of required material (A&B)	D Labor & Overhead Contribution
$45/lb.	$200/lb.	$14.40/lb. (7.2%)	$30.60/lb. (15.3%)	$11.25/lb. (5.6%)	$143.75/lb. (71.9%)
$30/lb.	$194/lb. (3% difference)	$9.60/lb (4.9%)	$30.60/lb. (15.8%)	$10.05/lb. (5.2%)	$143.75/lb. (74.1%)
$22.50/lb	$191/lb. (4.5% difference)	$7.20/lb (3.0%)	$30.60/lb (16.0%)	$9.45 (4.9%)	$143.75 (75.3%)

* Since composites are lighter weight than aluminum and complex parts are more labor intensive, Composite finished part costs can range from $200/# to more than $2000/#.

3M

Addressing Requested Items of March 31, 1995 Letter

Resin Options:	Fluorene epoxy family provides systems from very tough to higher temp performance with same chemistry and backbone.
Processing Parameters:	Large parts/injection times are solved with tooling and processing concepts.
Availability/Production:	In production
Physical & Mechanical Properties:	See 3M PR 500 Technical Data Sheet
Government Regulations:	With its new chemistry, PR500 has overcome restrictive regulations with the EPA. Its new chemistry has been extensively tested. Safety and health test results are extremely favorable and the EPA canceled the restrictive consent order on the curative. EPA requirements discourage new chemistry.
Quality Control:	3M Facilities audited and approved by many major Aerospace OEM's.

3M

When to Use RTM for Aerospace

- **Preconditions that must be satisfied**
  - Composites are desirable
  - RTM Resin meets design criteria
  - Match-metal tooling is required or affordable

- **Six Major Reasons RTM Process is Selected**
  - Manufacturing cost reduction
  - IML & OML high tolerance is essential
  - Significant part count reduction
  - Total part cost is less than metal concept
  - Make high complexity parts when prepreg cannot
  - Gain working experience for future applications

3M

TACKIFIER/RESIN COMPATIBILITY IS ESSENTIAL FOR AEROSPACE GRADE RESIN TRANSFER MOLDING

Jeff L. Kittelson and Steven C. Hackett
3M Aerospace, Industrial Tape and Specialty Division
3M Center / Building 209-1C-22
St. Paul, Minnesota 55144

ABSTRACT

Resin Transfer Molding (RTM) is rapidly being adopted by the aerospace industry as a key low cost, high potential composite manufacturing method for primary and secondary structures. A necessary requirement for the production of complex structures by RTM is the use of a tackifier, which serves to hold the preform together for handling at a reduced bulk factor prior to insertion in the closed cavity tool. Several tackifiers with widely varying chemistries are currently being evaluated for use in this process. This paper will describe potential problems caused by the use of tackifiers with different chemistries than the parent matrix resin. The advantages of using a tackifier with the same chemistry will also be highlighted. Compatibility and migration effects of the tackifier should not be disregarded unless the tackifier and RTM resin are the same chemistry.

KEY WORDS: Tackifier, Resin Transfer Molding, Preforms.

1. BACKGROUND

1.1 Tackifier Role. A key requirement in resin transfer molding (RTM) complex aerospace parts is to have a method of holding discrete graphite or glass plies together. This process is commonly referred to as making preforms. Preforms can be produced using inexpensive tooling that reflect nearly the exact shape of the finished part. Figure 1 illustrates a C-Spar preform made using a wood mandrel. Preforms handle as one body that can be easily and accurately placed into high precision RTM tooling rather than having to deal with cumbersome discrete plies of fabric broad goods. Some types of preforms can be produced by automated manufacturing methods using braiding or weaving. Interweaving of the rovings (or yarns) serves as the means to hold the preform together. The most common method is to apply tackifying materials (referred to as tackifiers) onto dry broad goods at various concentrations; typically ranging from four to seven

per cent. This paper will concentrate on the various tackifiers used and their influence on the cured RTM laminate.

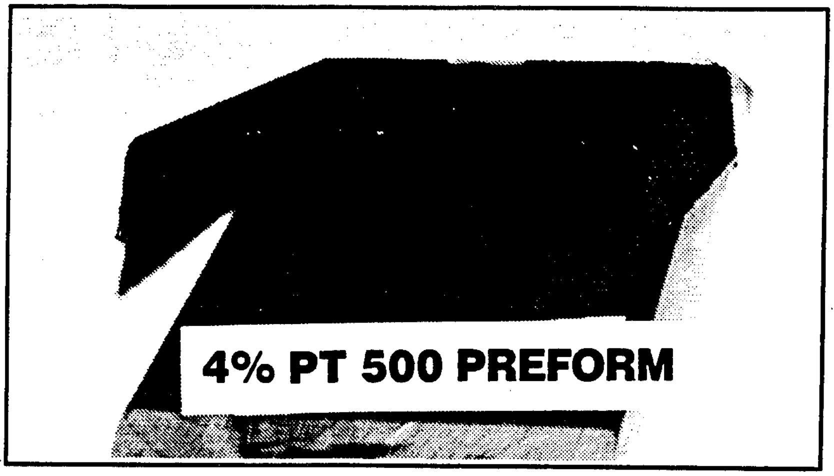


Figure 1 - C-Spar Preform Formed to Shape and Ready for RTM

<u>1.2 Types of Tackifiers and Application.</u> The two most common types of binders or tackifiers are low melting thermoplastics [1] and uncatalyzed thermosets [2] which can be applied using various methods. Common methods utilize veils, solvent spray and powder. Veils can be placed between adjacent plies of broad goods followed by fusing the ply stacks with heat and pressure to form a preform. The above tackifiers can be applied from solvents by spraying onto each broad good. This method is typically performed as the preform is being made and not as part of a pre-step manufacturing process for a roll of broad goods. Solvent removal and tackifier uniformity can be difficult to assure.

A preferred tackifier application approach is to use powders. Powders can be applied by hand but this is usually practiced for research and development purposes only. Typically, powders are uniformly applied per specified concentrations and melted to one surface of a continuous roll of broad goods. Tackified broad goods can be thought of as a very low resin content prepreg that can be made into ply kits using conventional automated broad good cutting equipment. Preforms can be easily made by stacking plies as desired and forming to near net part geometry using inexpensive tooling with moderate heat and pressure; such as a heated vacuum table or a press. Once preforms are made, they are ready to be placed in the RTM mold and resin injected.

It is important to recognize that graphite broad goods tackified at concentrations of five per cent (by weight) equates to ten per cent of the total resin in the finished RTM part. Due to the fact that the tackifier can become a major component of the matrix resin, the next Sections will address tackifier compatibility, concentration, and migration.

2. TACKIFIER COMPATIBILITY

2.1 Tackifier Selection. Tackifier compatibility is very important since an incompatibility of tackifier and RTM resin will reduce composite mechanical properties. Three materials were selected for study representing the following classes; a low-melting polyester thermoplastic, a non-catalyzed solid epoxy and a catalyzed solid epoxy. Each of these materials is a free flowing solid powder suitable for tackifying fabric broad goods by heating above their softening temperatures. The first two materials have the characteristic of not being chemically affected by repeated excursions above their softening temperature. Since they are not the same chemistry as the parent RTM resin, there is a question as to the degree of compatibility these systems possess.

The three materials selected for evaluation as tackifiers are Atlac® Polyester resin 32-626, Tactix® 226 Performance Polymer and 3M PT 500 Powder Tackifier. The Atlac® material is an ethoxylated bisphenol-A fumurate polyester available from Reichold Chemicals. This low-melting amorphous thermoplastic has traditionally been utilized as a binder for fiberglass preforms and more recently it has been considered for advanced, carbon fiber applications. Tactix® 226 from Dow Chemical is a high molecular weight solid epoxy. PT 500 is a product which was developed to be totally compatible with 3M PR 500 RTM Resin.

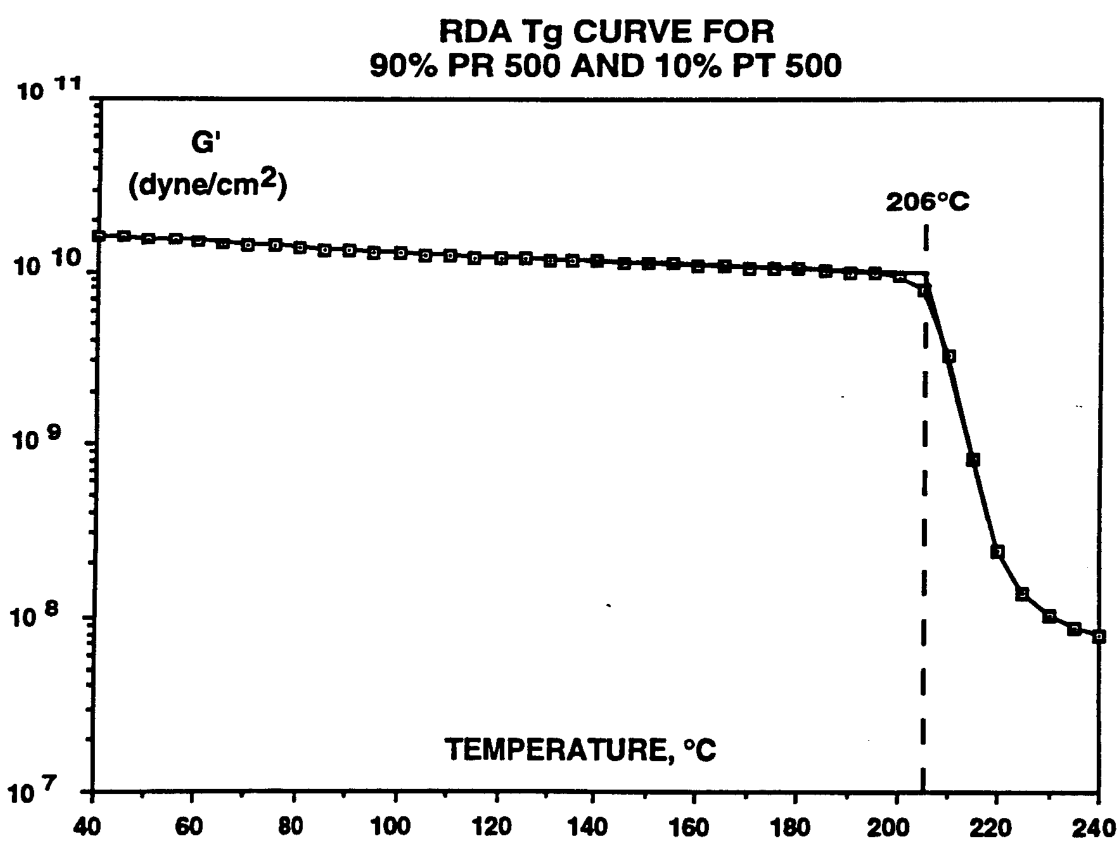


Figure 2 - Representation of RDA G' Curve showing "Tg Knee"

2.2 Method of Measuring Compatibility. While many chemical and physical properties could be evaluated to measure compatibility, perhaps one of the most important and easiest to measure is the glass transition temperature (Tg). Glass Transition temperatures were obtained by the torsion rectangular version of SACMA SRM-18 in which the Tg is defined as the intersection of two slopes "forming a knee" of the storage modulus plotted as a function of temperature (see Figure 2). Neat resin plaques were prepared by dissolving 5, 10 and 20 per cent (by weight) of each tackifier in PR 500 and curing each of these blends at 350°F in an aluminum mold. A machined neat resin sample is heated from 40°C to 240°C at 5°C/minute. Figure 3 shows the results of this evaluation.

2.3 Effect of Tackifier on Resin Properties. The reduction of Tg's at higher levels of Tactix® 226 and Atlac® tackifier in PR 500 are not unexpected. Although the Tactix® 226 material is an epoxy functional resin, and as such is capable of co-curing with the amine cured PR 500, the presence of increasing levels of this material will affect the stoichiometry of the resin formulation and the ability to achieve complete mixing of the two materials. Secondly, the specific chemical structure of the Tactix® 226 is different than the epoxy portion of PR 500 so different mechanical properties are expected. The addition of Tactix® 226 to PR 500 without the addition of the appropriate level of amine will potentially affect numerous properties including resin modulus, toughness, solvent resistance and as shown in Figure 3; Tg. The more drastic reduction in Tg of the Atlac® containing formulations is likely due to the plasticization of the matrix by the low Tg (Tg = 59°C) of the polyester thermoplastic. Since only one glass transition temperature was observed, it is expected that the Atlac®/PR 500 blends have cured to a homogenous, single-phase blend where the Tg is reduced significantly with increasing amounts of tackifier. PT 500, because it is the same chemistry as PR 500 shows no effect on Tg with increasing levels.

Another property which may be impacted by the addition of tackifier is solvent resistance. The Tg's of samples containing 10% of each tackifier after a 14 day exposure to water, Skydrol® LD-4 hydraulic fluid and JP4 jet fuel by immersion at 160°F are shown in Figure 4.

This data shows that the Tg's of these systems are relatively unaffected by Skydrol® and JP4, however, Tg is affected in each system by exposure to moisture. Figure 5 shows samples with 5, 10 and 20 per cent of each of the tackifiers in PR 500 after a 14 day exposure to moisture. Again, the PT 500/PR 500 blend is unaffected while each of the other systems show reduction in wet Tg with increasing levels of tackifier.

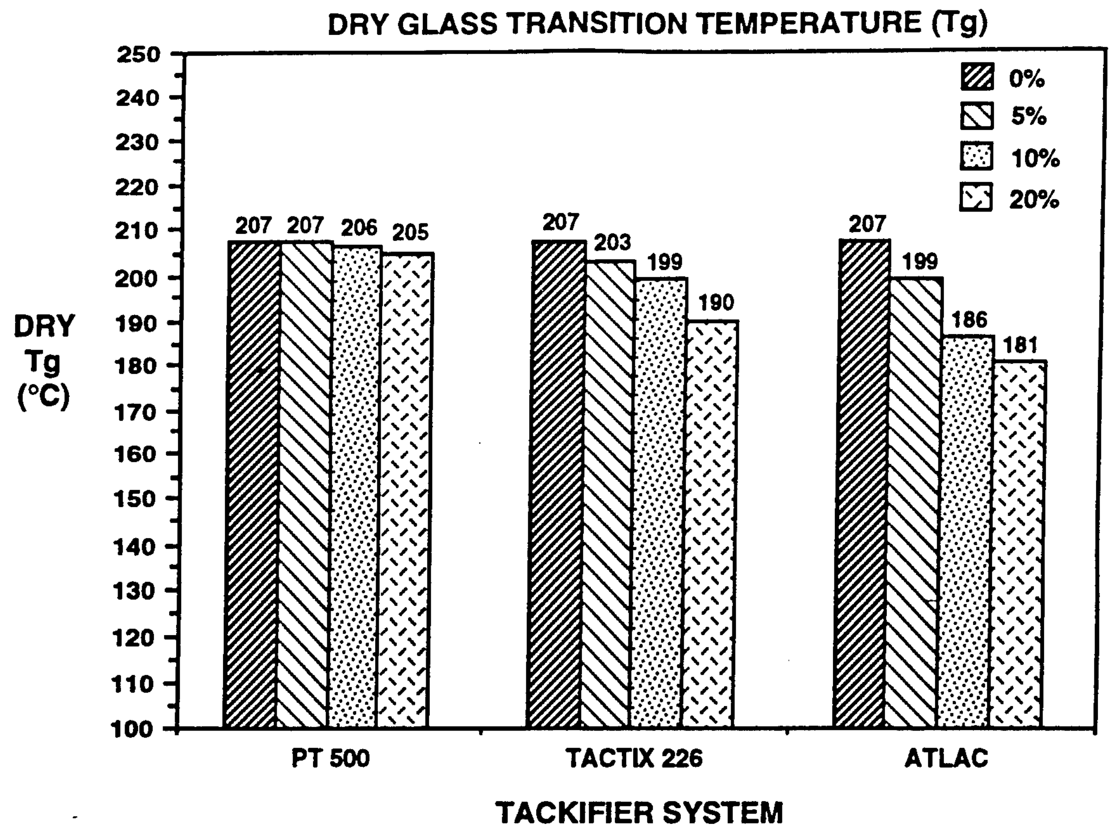


Figure 3 - Non-Compatible Tackifiers Continually Reduces Tg with Increasing Concentrations

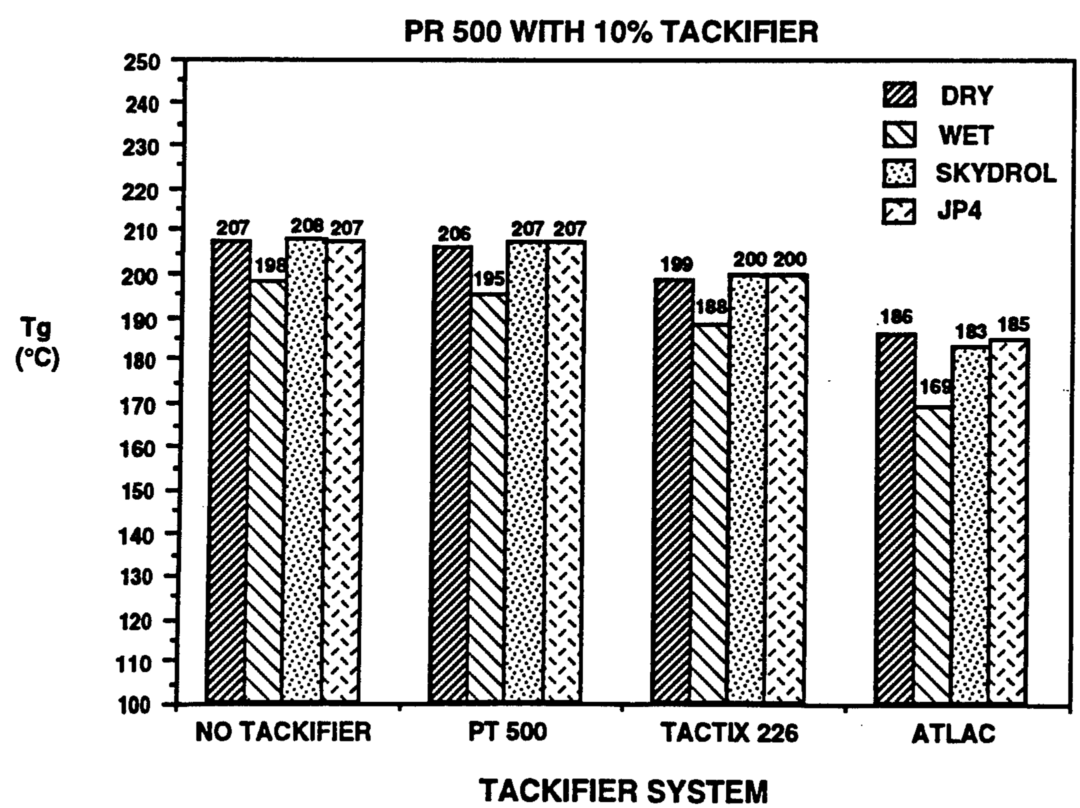


Figure 4 - Moisture Appears To Be Most Detrimental Fluid

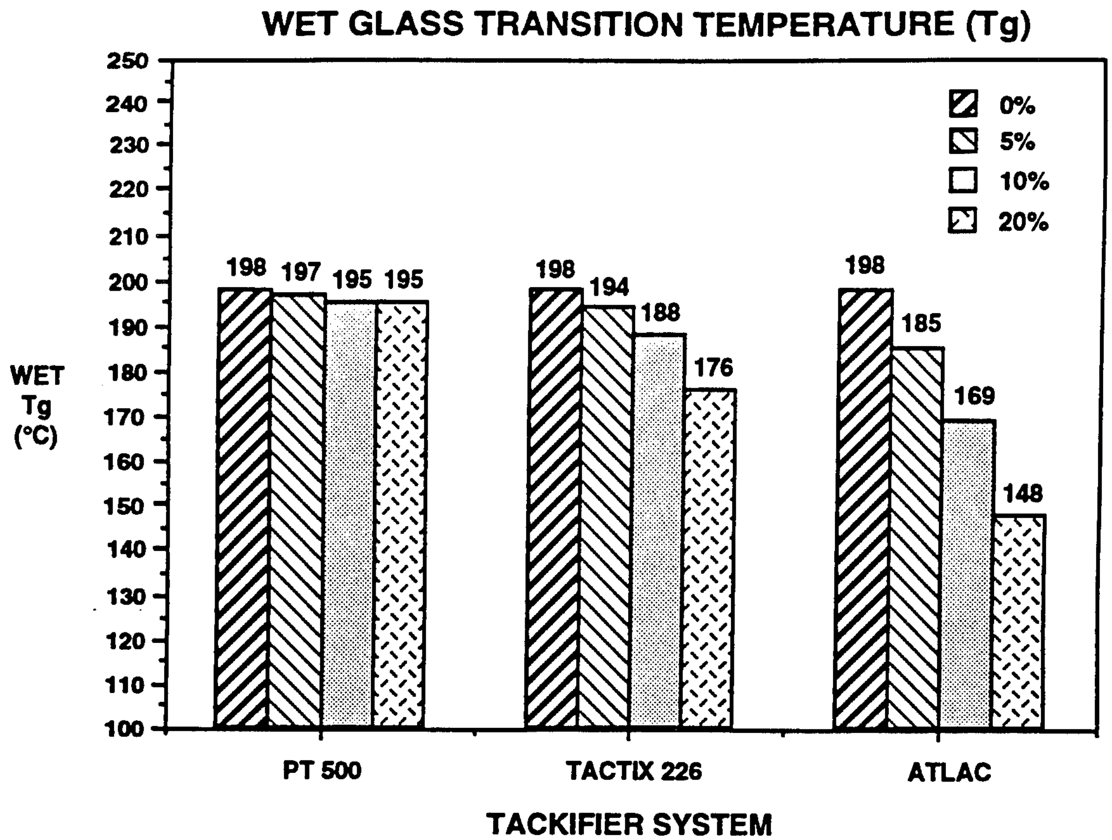


Figure 5 - Water Amplifies Effect of Non-Compatible Tackifiers

2.4 Effect of Tackifier on Laminate Properties. The above data shows the effect on Tg by "non-compatible" tackifiers. Many other properties may also be affected. It is probable that while these tackifiers are soluble in PR 500, they may not be fully mixed with the RTM resin upon injection. The effect of this uneven distribution within the laminate on the fiber/resin interface may be detrimental. An example of where this phenomena may have occurred is illustrated in Figure 6. Hercules IM7 eight-harness-satin fabric preform coated with 4% PT 500 and 4% Tactix® 226 were injected by the RTM process with PR 500. In-plane shear was tested in accordance with SACMA SRM-7; ±45° tensile. In-plane shear strength was selected as the screening test because it evaluates resin and resin-to-fiber interfacial performance. Typically, if shear performance degrades, then other key design properties will most likely be affected. The shear strength and modulus values are both degraded with Tactix® 226 compared to PT 500.

3. TACKIFIER MIGRATION

The previous section shows that increasing levels of "non-compatible" tackifiers can reduce the effective Tg of the material and thereby affect the physical and mechanical performance of the RTM composite. The next issue to evaluate is the potential for tackifiers to migrate. If migration occurs, property retention will continue to decline as increased concentrations of tackifier are formed or

deposited by the resin flow path. RTM panels were evaluated for migration occurrence by mechanically evaluating specimens along the flow path from resin entrance to exit.

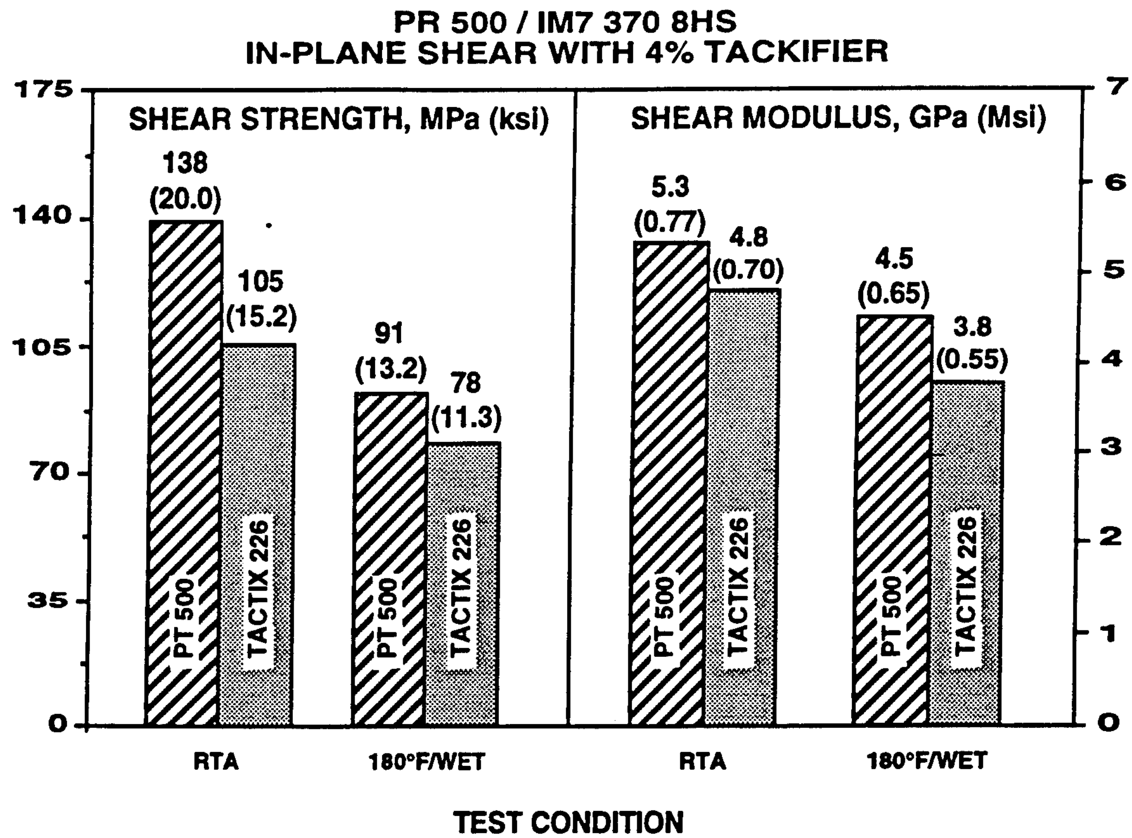


Figure 6 - In-Plane Shear Reveals Non-Compatible Tackifier Problem

<u>3.1 First Case Study.</u> One indication that migration occurred during the RTM process is shown in Figure 7. Two panels were made where resin was injected along the left edge and flowed to the exit located along the right edge of the panel. Each panel was constructed using AS4 plain weave fabric and PR 500 RTM resin. The first panel was tackified with four per cent PT 500 and the second was tackified with four per cent Atlac®. Glass transition temperature (same procedure as described in Section 2.2) was measured along the flow front. Figure 7 shows no significant loss of Tg (averaging 198°C) along the flow front for the panel tackified with PT 500. This does not indicate whether migration occurred because as described in Section 2, PT 500 is the same chemistry as PR 500 and therefore is completely compatible at any concentration. The four per cent Atlac® panel shows signs that migration occurred because the Tg continually decreases from 198°C at the entrance of resin to 187°C at the exit. Section 2.2 showed that increasing concentrations of Atlac® reduced the dry Tg values. The implication is that progressive lowering of Tg across the panel is caused by Atlac® binder migrating with the flow path producing increasing levels of tackifier in the test specimens.

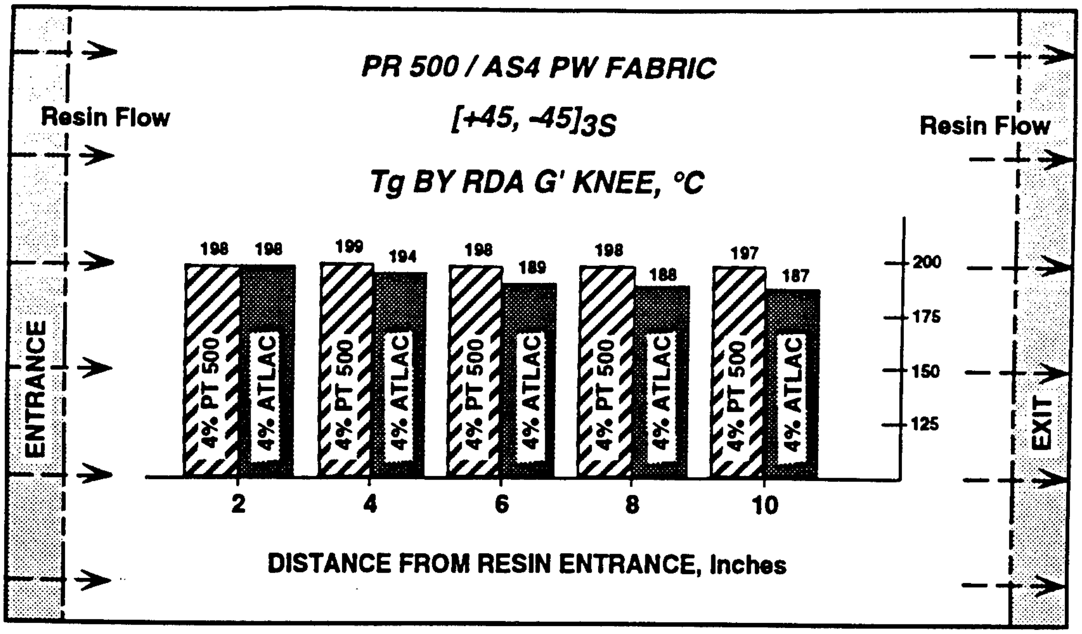


Figure 7 - Migration of Tackifier Is Shown By Tg Reduction

<u>3.2 Second Case Study.</u> Another example of tackifier migration occurring is shown in Figure 8. An in-plane shear panel was produced using a preform of which half was spray tackified with Stypol® 44-6020 (acetone solution of unsaturated polyester which is chemically similar to Atlac®) to generate tackifier concentration of five per cent. Resin was injected around the entire periphery and exited out the center. The construction of the panel was six plies of AS4 370 8-harness-satin fabric with a lay-up of [+45,-45,+45,-45,+45,-45]. The individual ultimate in-plane shear strengths as well as Tg progressively declined as a function of the flow path. The results shown in Figure 8 indicate that the Stypol® migrated from the edges of the panel to the exit. The non-tackified half of this panel showed no shear strength loss across the flow path except for the specimen located near the center. Because this particular specimen was located near the tackified section, a slight amount of Stypol® could have migrated and influenced this specimen's shear performance. Further, the initial property reduction caused by the Stypol® (the first specimens from each side; 17.5 versus 20 ksi) reaffirms that tackifier compatibility is very important to assure no performance degradation with or without compounded migration effects.

The above two examples show the possibility for tackifiers to migrate in flat, laboratory laminates. Under production conditions where complex shaped parts may be fabricated under higher injection pressures and flow rates, there is the possibility that the migration effect may be more pronounced. In cases where tackifier levels of 20 or 30 % (by weight) may accumulate, the need for resin/tackifier compatibility is crucial. This uncertainty of tackifier levels in discreet segments of composite structures make qualification of a matrix resin

system to an aircraft specification very difficult. The certainty of no property reductions by the use of a compatible tackifier alleviates migration concerns.

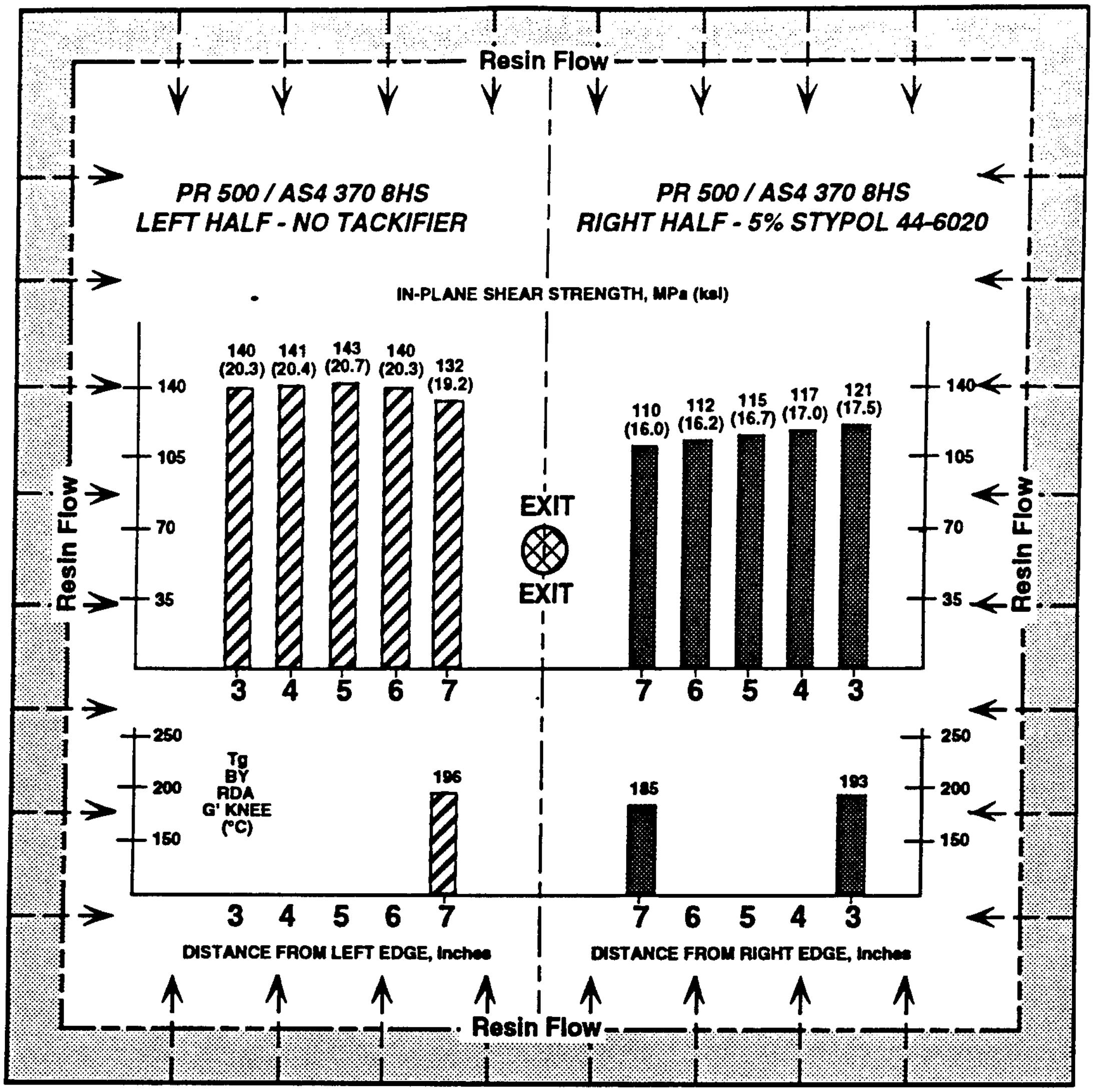


Figure 8 - Tackifier Migration and Non-Compatibility Dramatically Reduces Mechanical Performance

4. PT 500 PROCESSING TECHNIQUES

4.1 Method of Application. The previous Sections discussed the need to use tackifiers that are the same chemistry as the parent RTM resin system. Therefore, 3M has recently introduced PT 500; a compatible powder tackifier for PR 500. Tackified fabric broad goods are readily available. The preform fabricator or RTM parts manufacturer can also produce PT 500 tackified broad goods by the following procedure:

1. The desired amount of PT 500 can be applied uniformly (or as preform geometry requires) to one surface of the fabric. The use of a sifter type apparatus to apply PT 500 powder is recommended.

Application of the powder should be performed in accordance with the PT 500 MSDS that provides information on the appropriate safety precautions.

2. The powder can be melted onto the fabric at a recommended temperature of 93°C (200°F) to 99°C (210F) for 30 to 60 seconds using a heating procedure that does not disturb the powder particles. Infrared lamps or non-circulating ovens are recommended.
3. After the fabric cools to room temperature, it can be examined to assure that PT 500 was not completely absorbed by the fabric and that sufficient amount is on the surface for adequate ply-to-ply adhesion.

The above tackifying procedure is a starting point to make PT 500 tackified fabric. This procedure has proven to be successful in producing "laboratory scale" preforms. Modifications to the above recommended processing parameters may be necessary.

4.2 Tackifier Concentration. The amount of tackifier to apply to fabric broad goods may also need to be optimized for each specific application. Nominally 5% by weight of PT 500 to each ply of dry broad goods is optimum. This amount was empirically determined by applying varying amounts of 1, 2, 4, 6, and 8 per cent to AS4 plain weave fabric per the above tackifying procedure and then forming the plies at 93°C (200°F) into C-Spar cross sections; dimensions of 203 mm (8 inches) in length with a 140 mm (5.5 inches) web and 25 mm (1 inch) flanges. The C-Spar lay-up consisted of six plies with the orientation of $[+45, 0, -45]_S$. The preforms produced by this experiment are illustrated in Figure 9. The nominal thickness of the preforms ranged from 1.47 to 1.52 mm (58 to 60 mils) for all tackifier amounts investigated. This yielded a bulk factor of 30 per cent over the desired cured-ply-thickness based on 57 per cent fiber volume. The lower levels of 1 and 2 per cent were insufficient quantities to provide adequate tackifying attributes. At the levels of one to two per cent, the plies on the outer flanges of the C-Spar never fully tacked together. Further, the 90° web to flange angle (see Figure 1) opened 30° to about 120° nominally (see Figure 10).

Four to six per cent was qualitatively assessed to be sufficient to produce good preform shapes representing the finished part geometry. Applying eight per cent seemed to be excessive because the preform was noticeably stiffer. Using concentrations greater than necessary may be more difficult to reform and/or higher injection pressures may be necessary during the RTM process due to less free volume available. Therefore, five per cent of PT 500 appears to be optimum.

In general, the lowest amount of tackifier necessary to produce quality preforms is recommended.

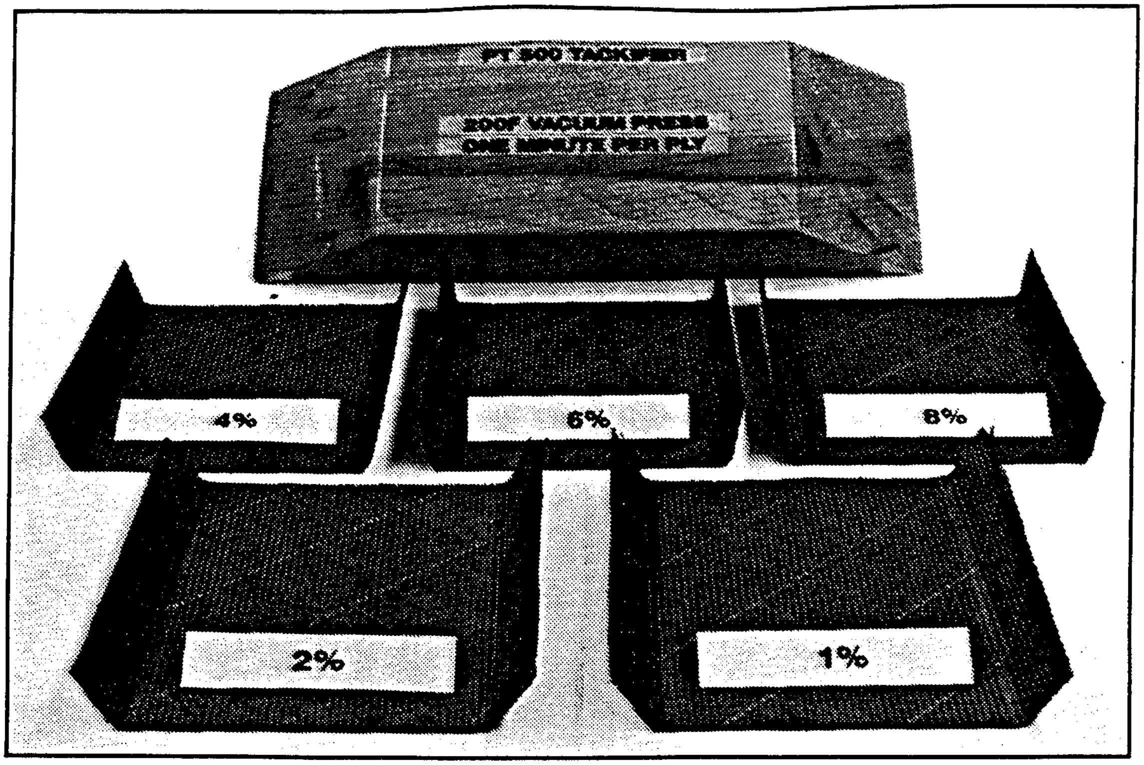


Figure 9 - Four to Six Percent of PT 500 Works Well as Tackifier

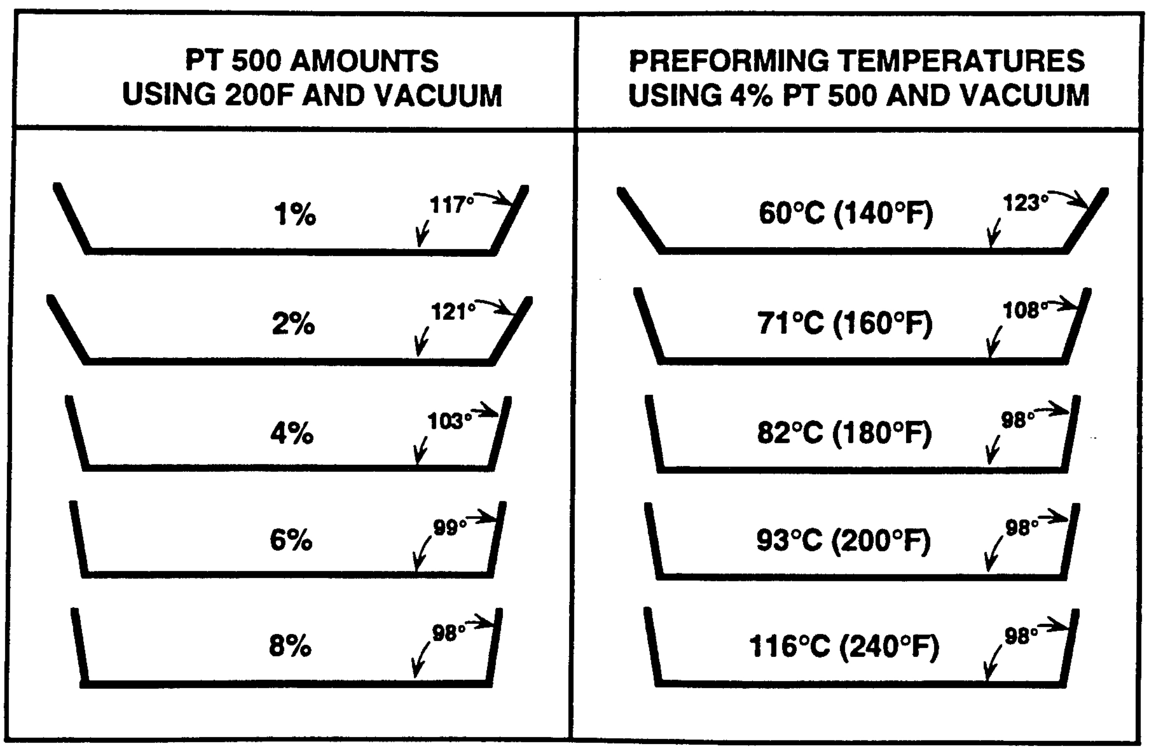


Figure 10 - Optimum Processing Shown by 90° Integrity of Flange

4.3 Making Preforms. Upon completion of application of the powder PT 500 tackifier to the broad goods the material is ready for the preforming process.

Processing PT 500 tackified broad goods into shaped preforms will require heat. The use of processing aids such as release paper that may transfer contaminants to the tackified material is not recommended. Evidence exists to indicate that if adjacent plies are ironed together using silicone release paper, the silicone transfers to the plies and can cause a reduction in mechanical properties governed by fiber-to-resin failure modes. High temperature release materials such as Teflon® coated films or peel ply are recommended if processing aids are needed.

The preforming process temperature for PT 500 was qualitatively assessed to be optimum between 82°C and 104°C (180°F to 220°F). The same approach was used as described above to determine the optimum tackifier level. Four per cent tackified AS4 plain weave fabric was processed into C-Spar preforms at various temperature levels using an infrared heated vacuum table. Temperatures of 60, 71, 82, 93, and 116°C (140, 160, 180, 200, and 240°F) were evaluated. For each temperature level, individual plies were formed to shape using 21 inches of Hg vacuum pressure for one minute. This procedure proved to be relatively efficient in producing preforms. The results of these temperature processing trials are illustrated in Figure 11.

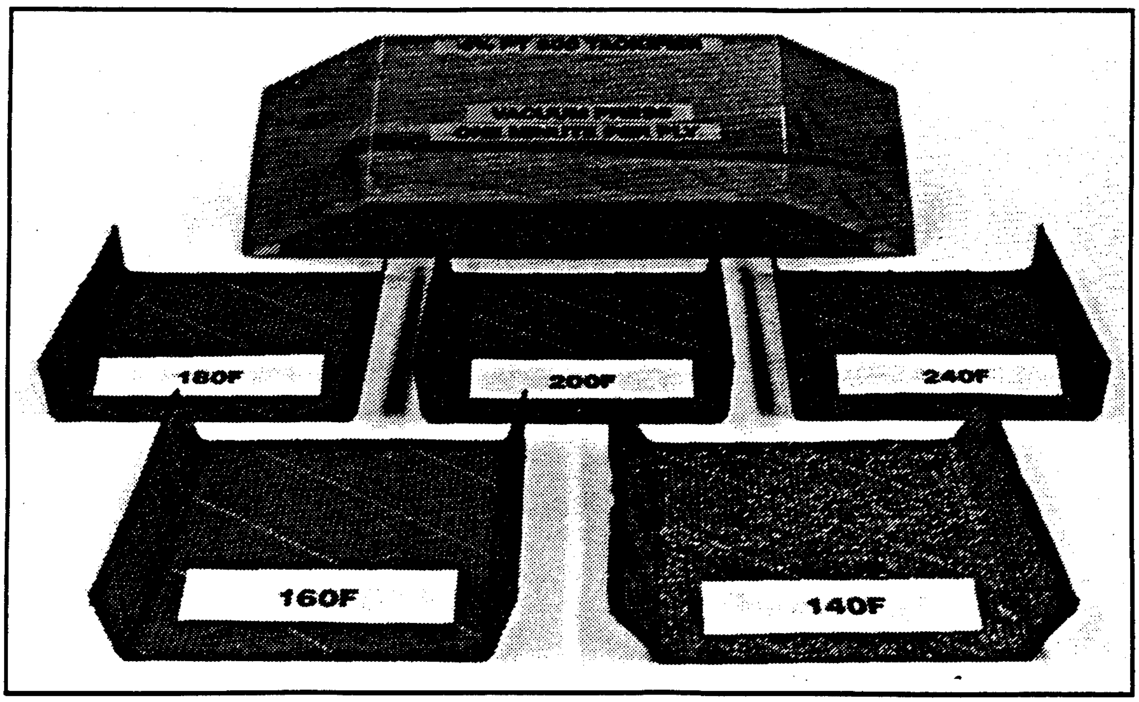


Figure 11 - Nominally 93°C Preforming Temperature is Optimum

The 60°C (140°F) processing temperature was clearly not adequate to tack the plies together to obtain the desired preform shape. Temperatures exceeding 60°C were sufficient to tack the plies together. The best preform shape integrity was achieved using 82°C (180°F) and higher as shown by Figures 10 and 11. The

preform processed at 116°C (240°F) was very "boardy" and this temperature was deemed to be excessive. On the basis of this study, preforming temperatures of 82°C to 104°C (nominally 200 ±20°F) is optimum. The lowest temperature to produce quality preforms repeatedly is recommended. Depending on the application, temperature trials may be warranted to optimize the preforming process.

5. PREPREG COMPATIBILITY FOR RTM

In a process similar to tackified fabric, RTM components have been successfully fabricated where SP 500-2 prepreg tape has been incorporated in the preform. Unidirectional prepreg is typically incorporated into RTM preforms where high stiffness is desired. Since the same chemistry is used in this product form, creative combinations of co-curing these compatible materials can be utilized in manufacturing high performance advanced composite components.

6. CONCLUSIONS

The compatibility of the tackifier and parent RTM matrix resin is essential for high quality aerospace composite components. The effect on resin properties and composite performance were shown to be negatively affected by the addition of a low-melting thermoplastic and a non-catalyzed solid epoxy; the two conventional tackifying materials for epoxy RTM resins. In addition, the migration of these tackifiers aided by the flow of the RTM resin was shown to be feasible. The mechanical properties will vary depending on the concentration of tackifier in the matrix resin. The level of migration could be dependent on part configuration resulting in domains of high tackifier concentration which can potentially dramatically degrade the mechanical properties of the composite laminate.

PT 500 was introduced as a tackifier which was developed specifically for the use with PR 500 RTM resin. PT 500 is effective at fabricating preforms at a level of 4 to 6 per cent by first coating broad goods followed by a compaction cycle at 200 ±20°F. Since the same chemistry is utilized in both the tackifier and parent RTM resin, no concern over compatibility, concentration, or tackifier migration is warranted.

7. REFERENCES

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2. a.) U.S. Patent Number 5,071,711 (December 10, 1991), Heck, H.G., and White, W.D.

   b.) U.S. Patent Number 5,217,766 (January 8, 1993), Flonc, N.P. and Brace, M.W.

8. ACKNOWLEDGMENTS

Dow/United Technologies Composite Products, Wallingford CT., has worked with 3M by providing some of the tackified fabric utilized in this study as well as some of the RTM cured laminates.

9. BIOGRAPHIES

Mr. Jeff Kittelson joined 3M's ITSD Aerospace Systems Laboratory in 1992. Previously he worked for General Dynamics Corporation for eight years. He received a B.S.C.E. degree from the University of Houston in 1984 and a M.S.M.E. from Southern Methodist University in 1990. Mr. Kittelson's current responsibilities include supervising a testing group, composite technical service and product development. Mr. Kittelson is presently the Treasurer of the Twin Cities SAMPE Chapter and has been an active member of SAMPE since 1985.

Steve Hackett received a B.A. degree in Chemistry from St. Cloud State University and a Ph. D. degree in Organic Chemistry from the University of Minnesota before joining 3M in 1985. Steve has worked since that time on the development of advanced composite products. He is currently a Product Development Specialist in the Aerospace Systems Laboratory of 3M's Industrial Tape and Specialties Division.

TECHNICAL PAPER

EM93-112

Advantages of a One-part Resin System for Processing Aerospace Parts by Resin Transfer Molding (RTM)

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abstract

One-part resin systems for RTM are being recognized as having several significant advantages over the more common two-part systems in use today. The advantages in processing include elimination of mix ratio concerns, reduction of in-process QC testing and reduction of worker exposure to chemicals. 3M Aerospace Materials Department offers a unique one-part resin system for RTM that provides additional advantages. The 3M PR 500 is deaerated during manufacture, thereby eliminating the degassing step and pumping directly from the shipping container is possible. The excellent stability of this one-part resin dramatically reduces waste and cleanup. Equipment for handling one-part systems will be discussed as well as a brief review of the unique characteristics and properties of 3M PR 500.

conference

Composites in Manufacturing '93
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Introduction

Resin Transfer Molding (RTM) is experiencing acceptance and growth in the Aerospace Industry in contrast to the downturn of The Industry as a whole. There is a growing realization of the economic advantages of the RTM process compared to conventional processes of autoclave curing and press molding. Many organizations are arriving at this conclusion. Evidence is the increased funding of RTM projects in most Aerospace Companies.

As organizations gain experience in the fundamentals of RTM, several are discovering ways of lowering the cost of the RTM Process itself. One of these ways, quickly coming to the forefront, is the use of a one-part RTM resin system. The major advantages will be discussed in this paper.

An outline of the basics of the RTM Process is illustrated in Figure 1. The process requires resin, resin dispensing equipment, a fiber preform and a closed heated mold. The resins are usually either one-part (premixed resin and curing agent) or two-part systems where the resin and curing agent come in separate containers. The dispensing equipment can generally be classified in one of three categories, (1) pressure pot, (2) two-part meter mix or (3) melt on demand unloading systems. Preforms vary from flat pieces of fabric laid in the mold, to complicated preforms of fabrics and fibers held in place by webs or "binders" of a thermoplastic nature, to braided structures in combination with any of the above. The mold can be constructed from a wide variety of materials. The particular part and application generally determine these details. Dimensional accuracy requirements, uniform heat distribution and projected life cycle are some of the factors to consider. Mold design is very critical and part specific and cannot be adequately addressed within the scope of this paper.

Each type of resin dispensing system will now be discussed.

Pressure Pot System

The pressure pot system [Figure 2] usually includes the following essentials, a pot with heated jacket, mixing provisions, air and vacuum lines to the chamber and plumbing to move the resin to the mold. The following process sequence might be typical for a two-part resin system:

Injection

1. Use recommended safety and hygiene equipment.
2. Open shipping containers.
3. Carefully weigh Part A and Part B into a third container or the heated RTM pot. A comfortable excess of resin must be mixed to insure completion of the injection in case of a problem requiring extra resin flow through the tool.
4. Mix thoroughly.
5. Degas the air from the resin included by the mixing process. This is done in the heated pressure pot with vacuum and mixing.

6. Collect sample to run Q.C. resin/curing agent ratio check.
7. Connect heated lines and apply air pressure to move resin into mold.

Cleanup

1. Clean the scale, mixing container and mixing paddles. The lines and valves from the pot to the mold must be purged, typically with the uncatalyzed base resin, followed by solvent washes. An alternative used by some, is to use a disposable liner in the heated hose (typically copper tube) and discard the liner after the injection.

Two-part systems are generally quite reactive and require close monitoring of process temperatures. The pot, line and valves must be cleaned and flushed with solvent to avoid polymerization. When clean up is completed there are containers of waste resin and dirty solvents to dispose of. Proper disposal of such materials is mandated by local, state and federal agencies. These are costly, but necessary steps in handling of two-part systems.

For a one-part resin system, steps 2, 3 and 5 above (weighing, mixing and QC sampling) may be eliminated. The degassing step is still necessary because of air entrapped while transferring the resin to the pressure pot.

A variation of the pressure pot system exists and is used successfully at some locations. This variation works such that after the resin has been placed in the chamber and degassed, a piston forces the resin into the mold, injecting like a large syringe. An advantage of this system is that one can have closer control of the injection pressure and flow rate through the use of hydraulics and pumps.

Two-Part Meter Mix System

A two-part meter mix system [Figure 3] usually consists of two holding tanks equipped with mixers and vacuum (for degassing), two metering pumps or pistons, a mixing unit and valving to allow ratio checks from the metering pumps and the mixing unit. A typical processing scenario with this type equipment is given below:

Injection

1. Use recommended safety and hygiene equipment.
2. Open the shipping containers.
3. Transfer Part A and Part B into their respective heated holding tanks.
4. Vacuum degas each tank. A mixer for agitation should be used for optimum deaeration.
5. Check and adjust ratio pumps for the critical chemical stoiciometry.
6. Check and adjust mixer to obtain uniform mixture. The mixing step is as critical as the ratio of part A and part B for a successful part. Q.C. samples are typically taken initially and periodically during the injection sequence.
7. Connect heated lines and provide adequate pressures to move resin into the mold.

Cleanup

1. The cleaning sequence is much like the previously described procedure for the pressure pot. In this case, the base resin is pumped through the system to purge the mixer thoroughly, as well as the lines.

Most two-part RTM meter mix equipment manufacturers indicate that with some minor modifications their equipment can be used to transport a one-part resin system to the mold. This mode of operation would be similar to the pressure pot handling of a one-part. Care must be taken to heat all sections of the equipment since most one-part resins are high viscosity liquids or solids at room temperature.

Pail Unloading System

A "Heat On Demand" pail unloading system [Figure 4] is the last type of RTM dispensing equipment to be discussed. This process seems most suited for one-part resin systems. The essential parts of this process are a heated platen with pump and heated line.

The scenario of a RTM process with this type equipment is very simple and as follows:

Injection
1. Use recommended safety and hygiene equipment.
2. Install shipping container as received, on pail unloader.
3. Set platen and hose temperatures.
4. Inject through heated lines.

Cleanup
1. No cleanup on the injection side of the mold is required for at least one of the one-part PR 500. Other one-part resins may require cleanup depending on manufacturers RT out time limitations.

Two-part resin systems can be used with this type equipment by weighing, mixing and degassing before installing on the pail unloader. A thorough cleanup would be required for the use of a two-part system as with the other equipment system.

Graco, Inc. is an equipment supplier that has suitable units for the 1, 5 and 55 gallon container sizes.

General Advantages of a One-Part

Some of the general advantages of a one-part RTM resin system in any of the above processing scenarios are as follows:

(For your Industrial Hygienist)

1. **No mess of mixing.**
2. **Less worker exposure to chemicals.**

(For your Quality Assurance Group)

3. **No mix ratio concerns.**
   a. Complete mixing is assured by the supplier.
   b. Chemical and physical Q.C. testing is complete before receival.

Additional Advantages Using 3M PR 500 and Pail Unloading Equipment

The following list of additional advantages are true for 3M PR 500 one-part resin utilizing a "melt on demand" pail unloading system.

4. **No transferring of resin is required**. Again, this is a point of comfort for the Industrial Hygienist.

5. **Pump directly from the shipping container**. The 3M PR 500 containers are the proper size to fit the available pail unloaders. Simply remove the top of the container and set the pail under the heated platen.

6. **No degassing necessary**. 3M PR 500 is thoroughly mixed under vacuum and carefully loaded into the shipping container to avoid air inclusion.

7. **Reduced heat exposure of the resin**. Only the resin at the surface of the container is in contact with the heated platen and will be greater than ambient temperature. The 3M PR 500 resin can be pumped easily at temperatures as low as 135°F and it's stability is several hours at temperatures less than 200°F. This excellent stability preserves the lowest possible viscosity and longest possible injection time.

8. **No pot life concerns.** The bulk of the resin remains at ambient temperature eliminating any concern of setting up in the pail or the equipment.

9. **No pump and hose clean-up, no solvents required.** Because of the shelf stability and the low temperatures required to process the 3M PR 500 resin through the delivery system, no clean-up of the pump or purging of the hose is usually necessary. Resin waste is nearly eliminated and no solvents are required. With increasing environmental controls, minimizing waste and solvent usage is recognized as a significant advantage at several companies.

Due to the exceptional storage stability of the 3M PR 500 resin, if a pail mounted on an unloader were not to be used for several weeks, it need not be removed and placed in cold storage. 3M PR 500 usually is kept in the injection equipment at room temperature and simply turned on to be injected as needed.

A typical injection set-up utilizing a "heat on demand" pail unloader is shown schematically in Figure 5. Important mold details may be seen. One such detail is the channel to carry the resin around the mold combined with the "waterfall" or weir area. This "thin film" weir area is very efficient in transferring heat to the resin, thus ensuring that the resin going into the preform is at the correct temperature and at it's lowest viscosity.

A summary of the resin characteristics of 3M PR 500 resin which make it advantageous for RTM:

3M PR 500 resin is:

A one-part RTM resin system
Room temperature storable (for 60 to 90 days or more)
Low viscosity (25-50 cps) at recommended mold injection temperatures

Low shrinkage during cure
Low exotherm during cure
Completely cured in two hours at 350°F
Inherently tough
High modulus
Low moisture absorption after cure

3M PR 500 in composite laminates gives properties equivalent or better than the state of the art advanced composite prepregs. (Reference 1, Reference 2)

3M PR 500 in composite form is:

Extremely tough with CAI greater than 40 ksi on carbon fabrics when using Boeing or SACMA test methods at 1500 in lbs./in. impact.

Suitable for Hot/Wet performance above 300°F

Superior fiber wet-out which provides low void content and high shear strength.

Summary

One-part resin systems for RTM are gaining the reputation of having several significant advantages over two-part systems. Nearly every group in a parts manufacturing organization can benefit. There are major advantages for Production, Industrial Hygiene, Quality Assurance and Structures Design group. General advantages summarized are: No messy mixing, less exposure to workers and no mix ratio concerns. When using 3M PR 500 RTM resin, additional processing advantages can be realized: no degassing, pumping directly from the shipping container, reduced heat exposure of the resin, no pot life concerns and virtually no clean-up required. Processing of one-parts can be accomplished by all common types of RTM machines. The "heat on demand" pail unloading system is particularly well suited for one-part resin systems.

3M PR 500 is a leading example of an advanced one-part resin system. It is well suited for the RTM process and the simple pail unloading procedure. This resin system also gives composite performance equivalent to or better than the latest advanced composite prepreg systems. 3M PR 500 has the unique combination of excellent toughness with hot/wet performance greater than 300°F. These properties allow the designer the latitude to design significantly lighter weight structures.

References

1. S. C. Hackett, P. C. Griebling, A High Performance Aerospace Resin for Resin Transfer Molding, 35th International SAMPE Symposium and Exhibition, Anaheim California, Volume 35, April 2-5, 1990, pp. 1398-1410.

2. S. C. Hackett, P. C. Griebling, A. M. Hine, Unique Advanced Materials With High Performance and Resin Transfer Molding Characteristics, 12th International European Chapter Conference of the Society for the Advancement of Material and Process Engineering, Maastricht, The Netherlands, May 28-30, 1991, pp. 21-31.

Figure 1

RESIN TRANSFER MOLDING (RTM)

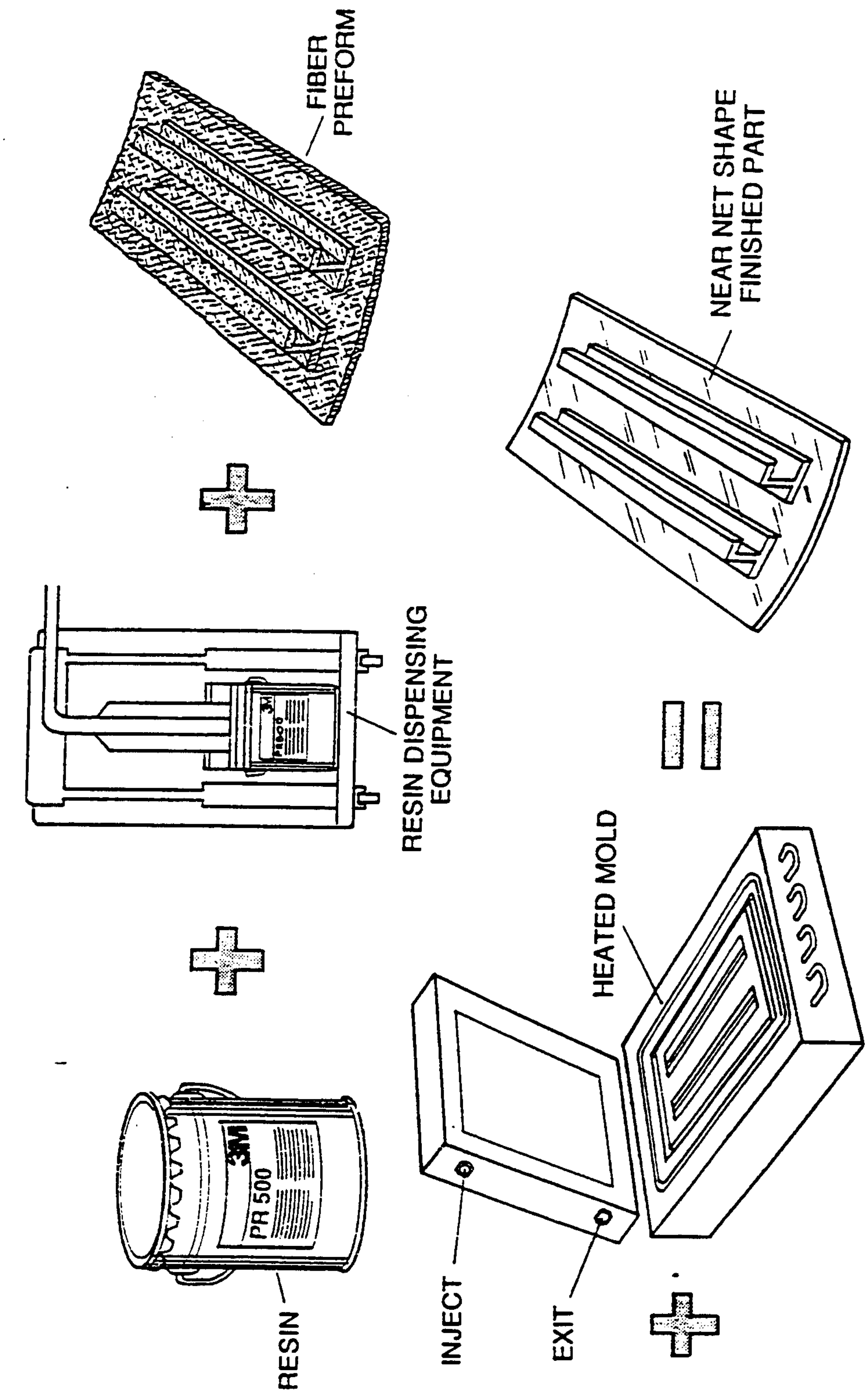


Figure 2

HEATED PRESSURE POT

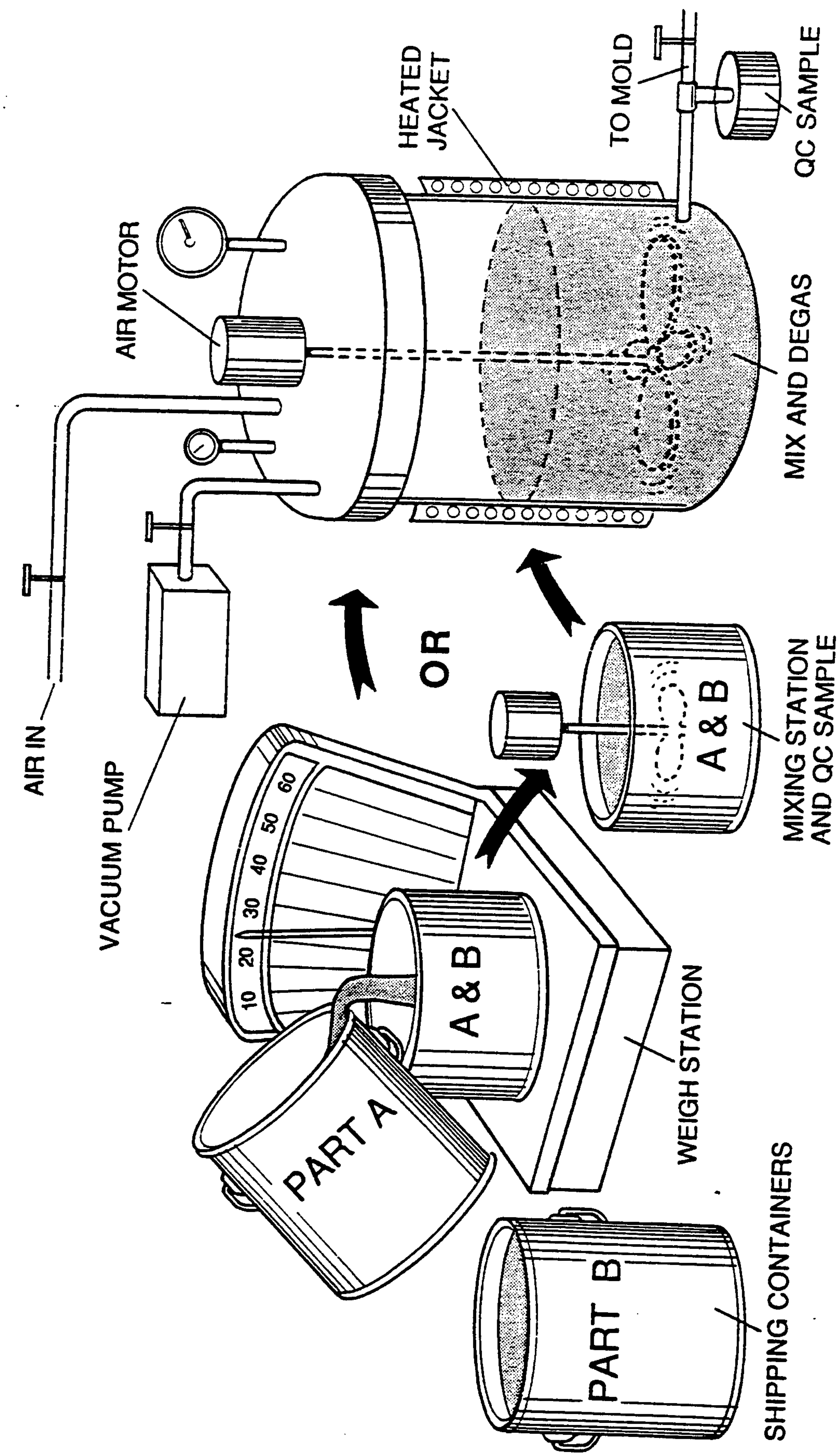


Figure 3

TWO-PART METER MIX EQUIPMENT

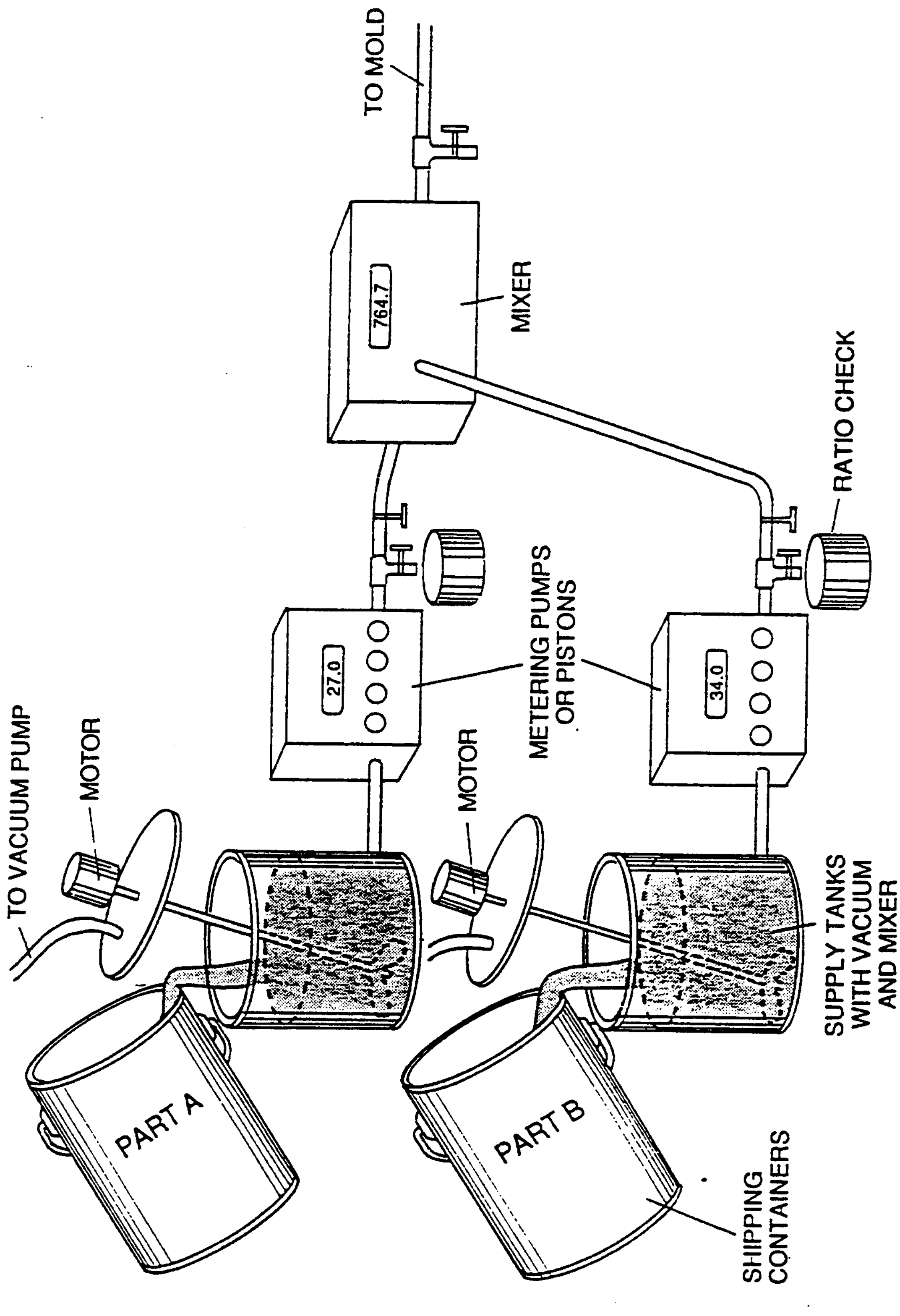


Figure 4

"MELT-ON-DEMAND" UNLOADER

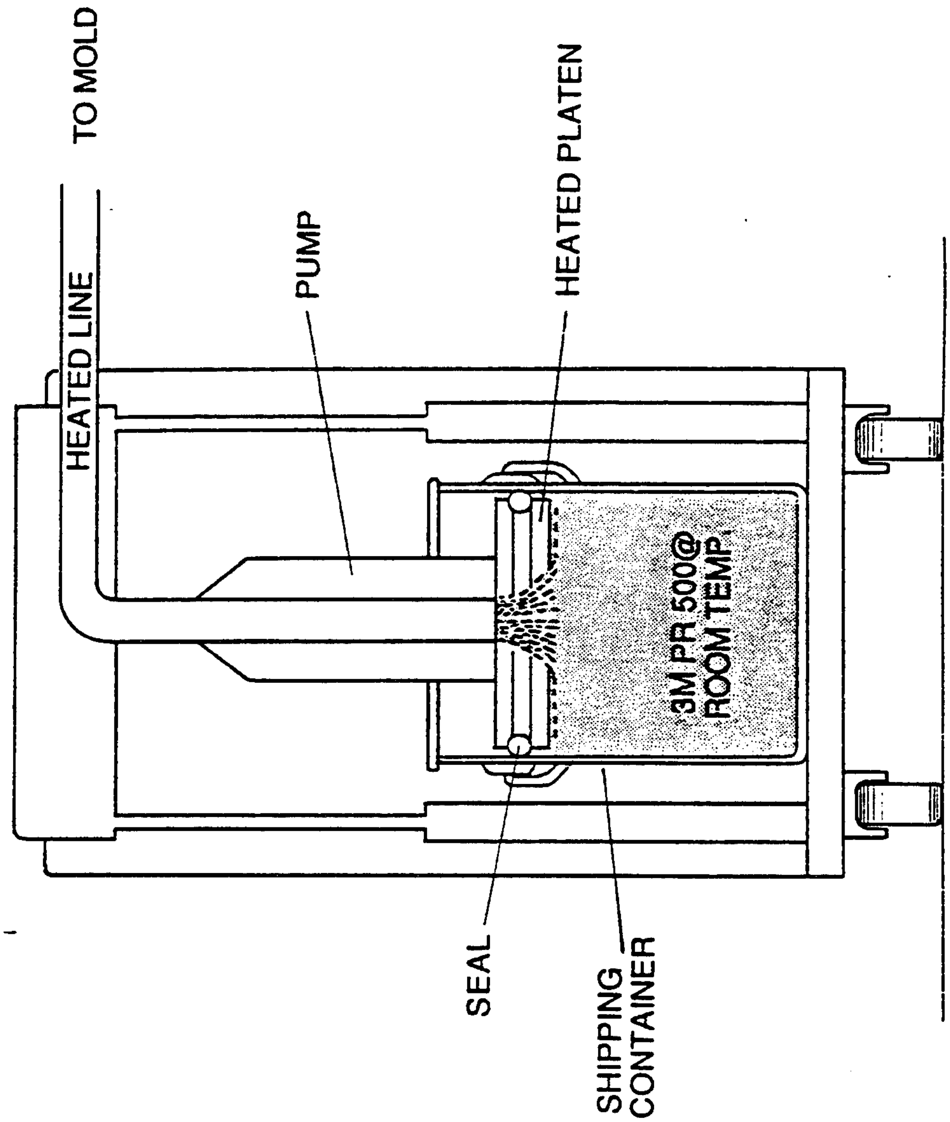
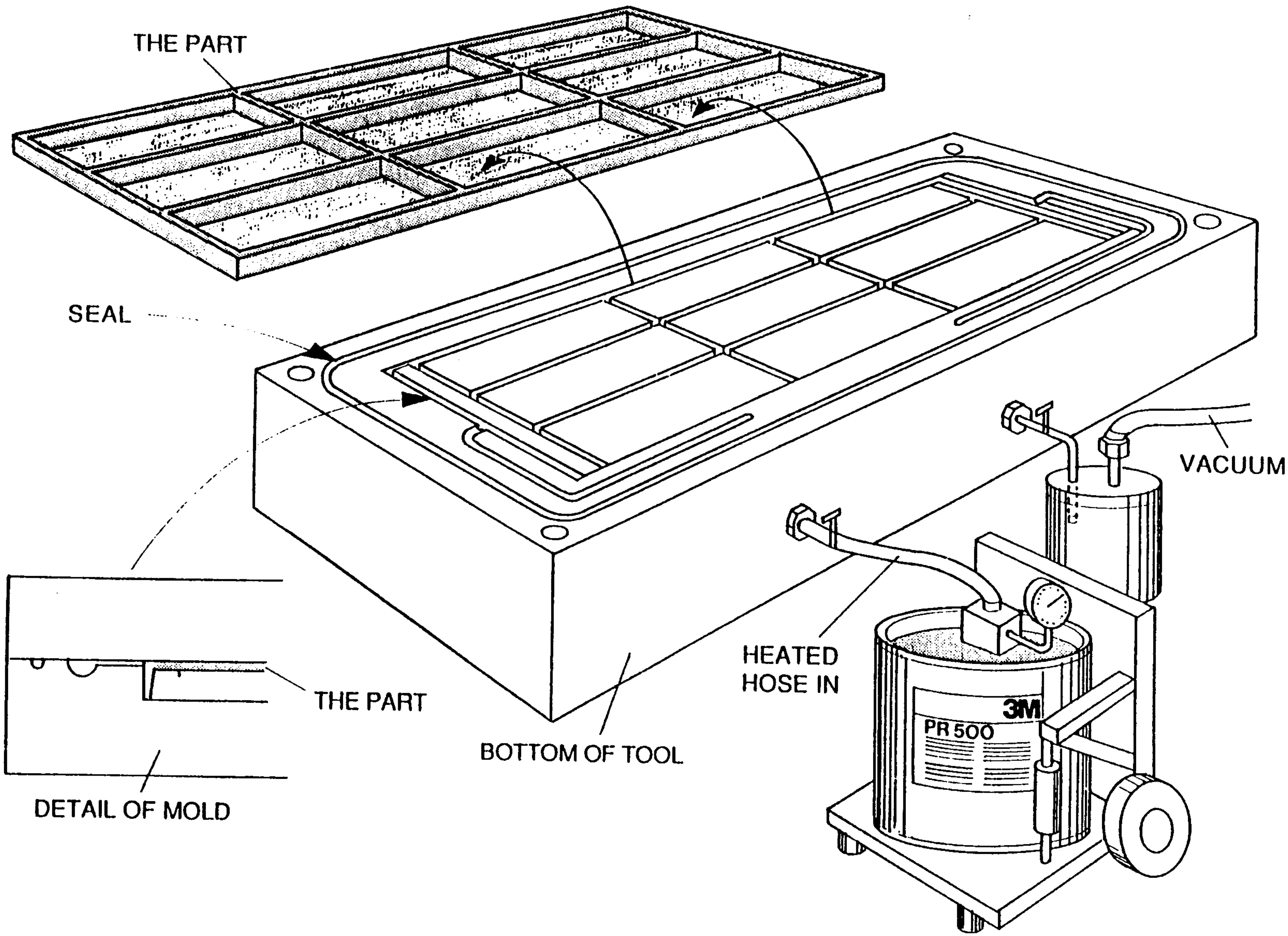


Figure 5

TYPICAL RTM PROCESS WITH PAIL UNLOADER



RESINS FOR RESIN TRANSFER MOLDING (RTM)

by

Andy Wang

CIBA POLYMERS DIVISION
ARDSLEY, NY 10502

Resins for RTM

Requirements for General RTM Systems

- Low viscosity
- Long pot life
- Good thermal/mechanical properties

Requirements for Advanced RTM Systems

- One-component system
- Toughened system
- Properties are equal or better than those of prepreg systems

Resins for RTM

CIBA carries a broad range of specialty resins, hardeners and resin systems

Resins	Hardeners
Bis-A Di-functional epoxies	Aliphatic Amines
Bis-F Di-functional epoxies	Cycloaliphatic Amines
Multi-functional epoxies	Aromatic Amines
Bismaleimides	Amides
Cyanate esters	Anhydrides
Polyimides	Catalysts
	Special Hardeners

Resins for RTM

Resin Systems to Review

- Two-component systems
  - (a) GY 282/HY 310
  - (b) MY 721/HY 5200

- One-component high performance system
  - (c) XU MV 723

- Developmental toughened system
  - (d) 93-104

Resins for RTM

(a) GY 282/HY 310

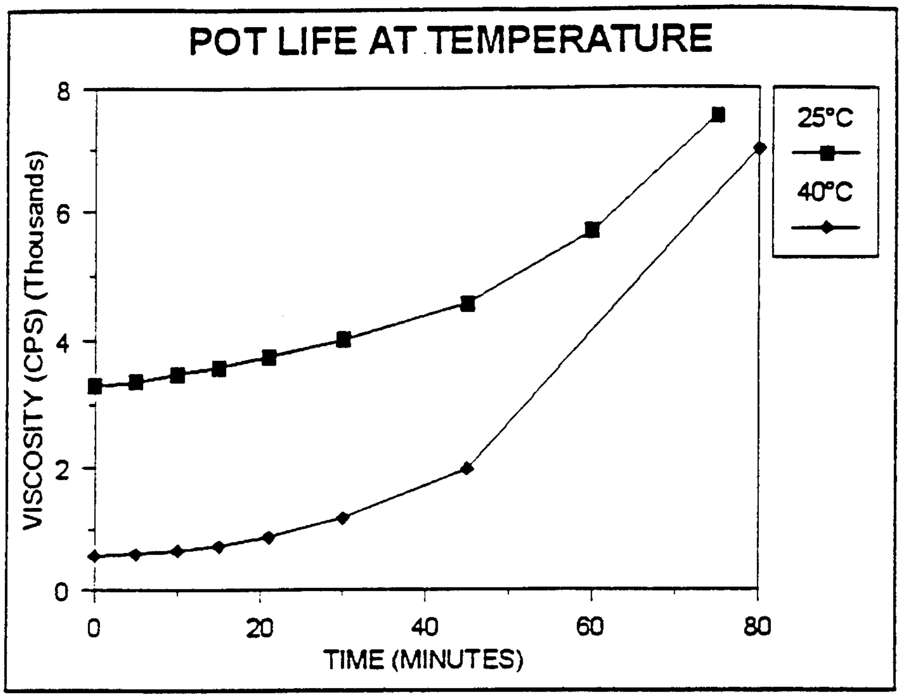
- A low viscosity, two-component, room-temperature processible system

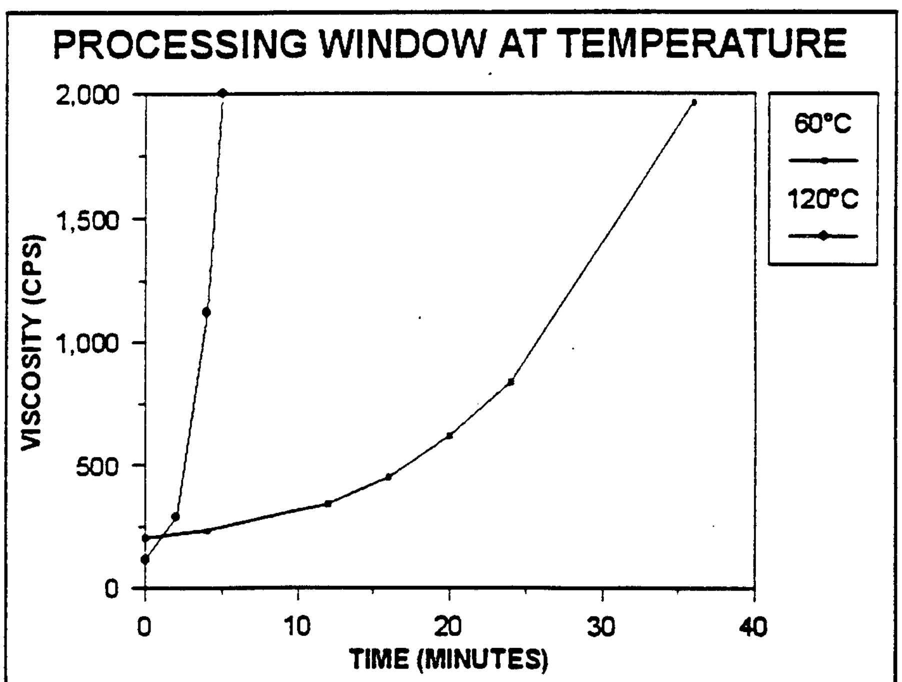
Typical Properties

	GY 282	HY 310
Appearance	Clear liquid	Clear brown liquid
Viscosity @ 25°C	3000-4000 cps	1200 cps
Epoxy Value	0.55-0.63 eq/100g	-
Active Hydrogen Eq.	-	58 g/eq.
Density	1.17 g/cm^3	1.04 g/cm^3

Resins for RTM

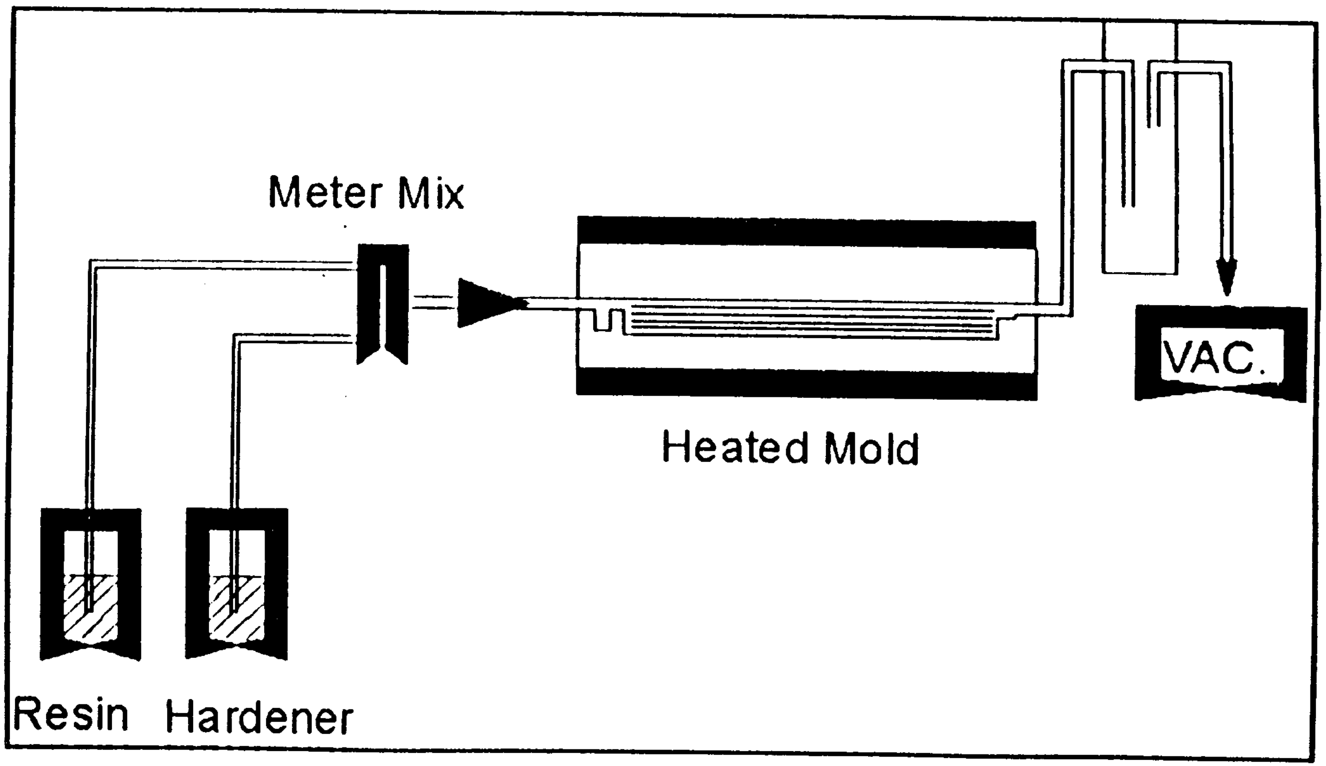
(a) GY 282/HY 310





Resins for RTM

(a) GY 282/HY 310



Resins for RTM

(a) GY 282/HY 310

Composite Properties

Table 3 and Figure 6 show some thermal/mechanical properties of GY 282/ HY 310 composite laminate with carbon fibers (Celion G30-500, 5 harness carbon weave, 54% fiber volume fraction). The laminate was cured for 30 min. at 80°C + 2 hours at 150°C.

Table 3

	AS4, 6K-135-5HS 380g/m^2
Tested at 23°C (77°F)	
Flexural Strength[1], KSI (MPa)	127 (876)
Flexural Modulus [1], MSI (GPa)	7.1 (49)
Short Beam Shear Strength[2], KSI (MPa)	9.7 (67)
Compressive Strength[3], KSI (MPa)	87 (600)
Tensile Strength, KSI (MPa)	113 (780)
Tensile Modulus, MSI (GPa)	8.4 (58)
Tested at 82°C (180°F)	
Flexural Strength, KSI (MPa)	85 (586)
Flexural Modulus, MSI (GPa)	6.2 (43)
Short Beam Shear Strength, KSI (MPa)	6.0 (42)
Glass Transition Temperature	
TMA[4] (°C)	127
DMA[5] dry (°C)	136
DMA wet[6] (°C)	133

Resins for RTM

(b) MY 721/HY 5200

Typical Properties

	MY 721	HY 5200
Visual appearance	Brown liquid	Brown liquid
Viscosity, cps	3000-6000 @ 50°C	160 @ 25°C
Epoxy Value (eq/100g)	0.86-0.91	--
Active Hydrogen eq.	--	44.5
Density, g/cm^3	1.17 (9.8 lb/gal)	1.02

Resins for RTM

(b) MY 721/HY 5200

Figure 3

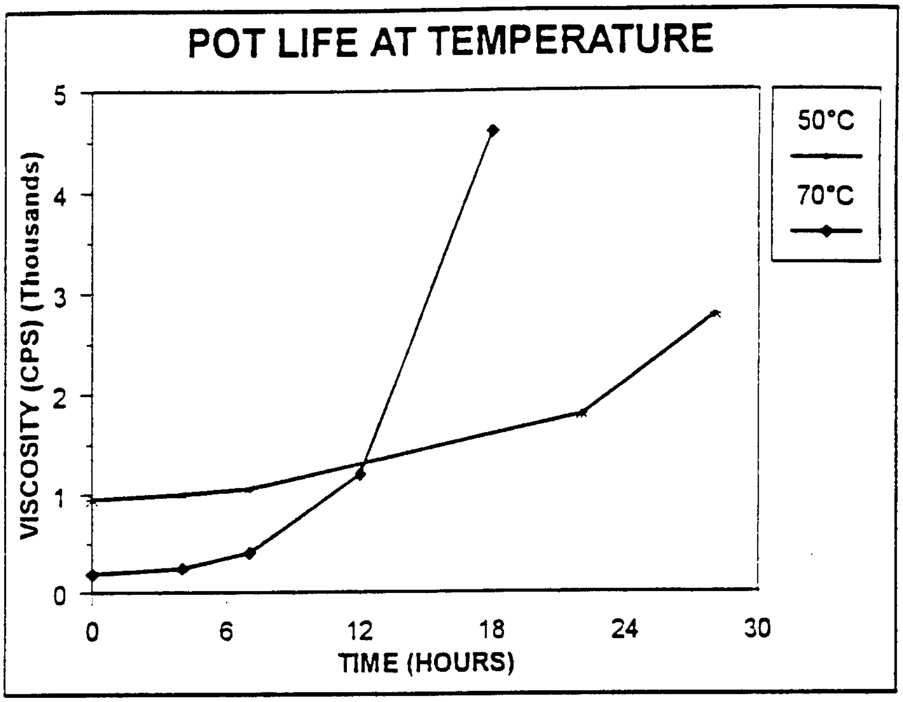
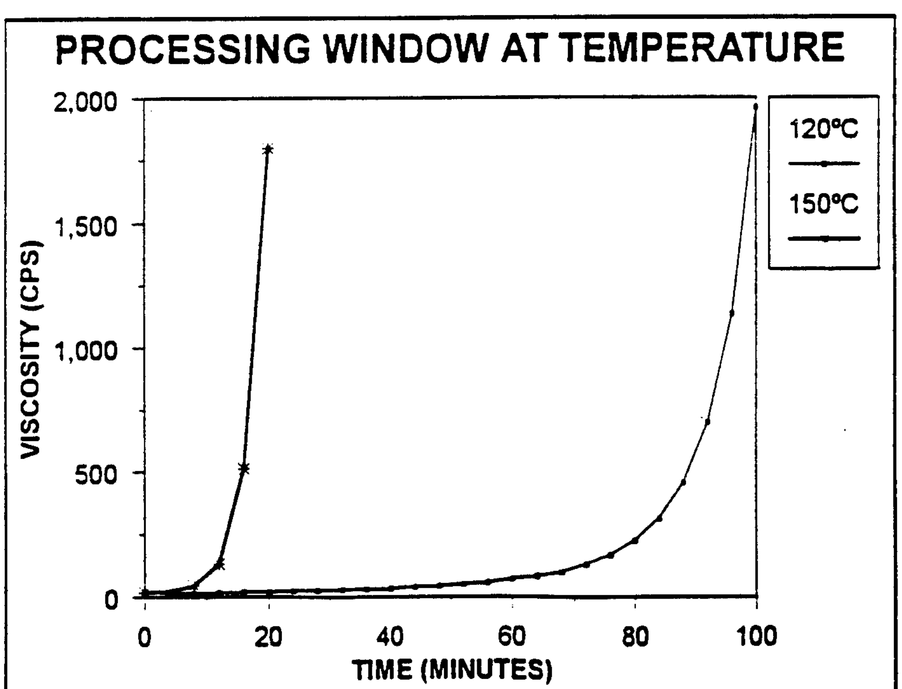
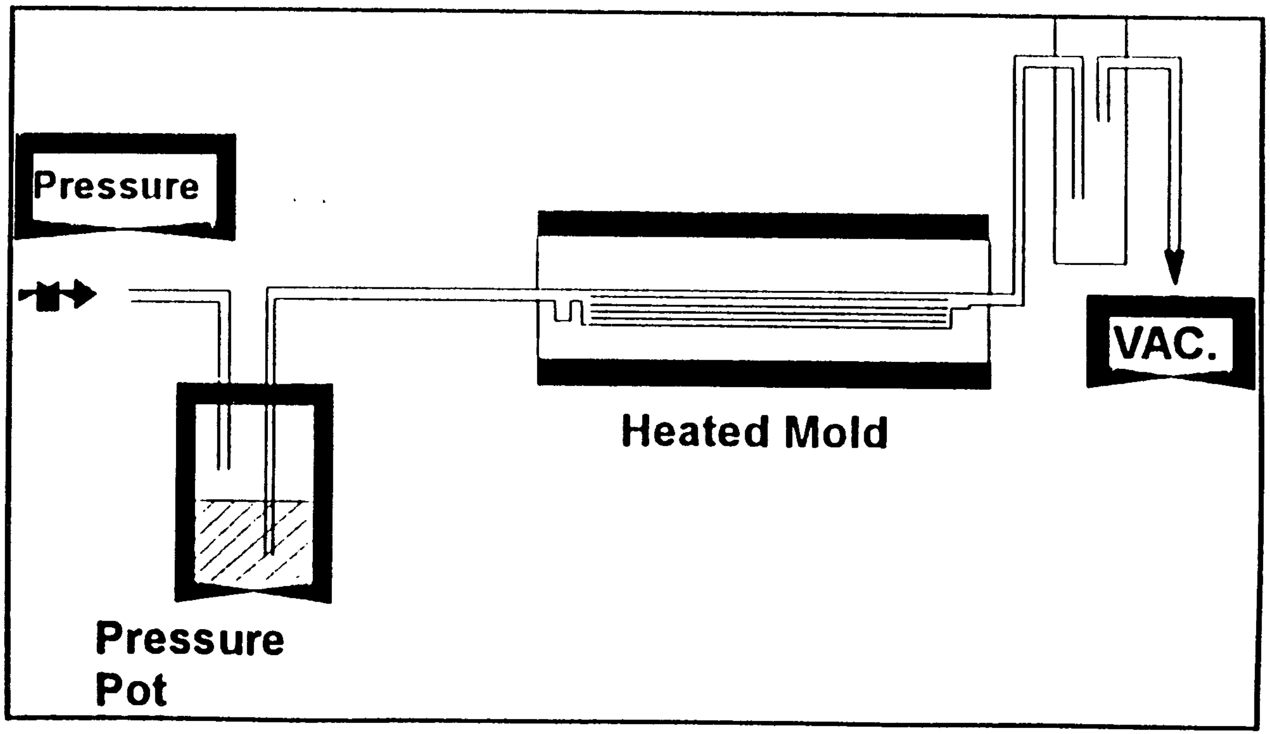


Figure 4



Resins for RTM

(b) MY 721/HY 5200



Resins for RTM

(b) MY 721/HY 5200

Composite Properties

Table 4 and Figure 6 show some thermal/mechanical properties of the MY 721/HY 5200 composite laminate with carbon fibers (Celion G30-500, 5 harness carbon weave, 54% fiber volume fraction). The laminate was cured for 2 hours at 177°C.

Testing Conditions	25°C (77°F)	121°C (250°F)	150°C (300°F)	150°C (300°F) Wet	177°C (350°F)
Flexural Strength[1], Ksi (MPa)	125	103(710)	100(690)	67(460)	88 (610)
Flexural Modulus, Msi (GPa)	(860)	6.4 (44)	6.4 (44)	5.6(39)	6.4 (44)
Short Beam Shear [2], Ksi (MPa)	6.9 (47)	8.0 (55)	7.6 (52)	5.4(37)	6.4 (44)
Compressive Strength[3], Ksi	9.0(62)				
(MPa)	100(690)				
Tensile Strength[4], Ksi (MPa)	89 (615)				
Tensile Modulus, Msi (GPa)	8.5 (59)				
Glass Transition Temperature					
TMA[5] (°C)	232				
DMA[6] dry (°C)	239				
DMA wet[7] (°C)	230				

Resins for RTM

(c) XU MV 723

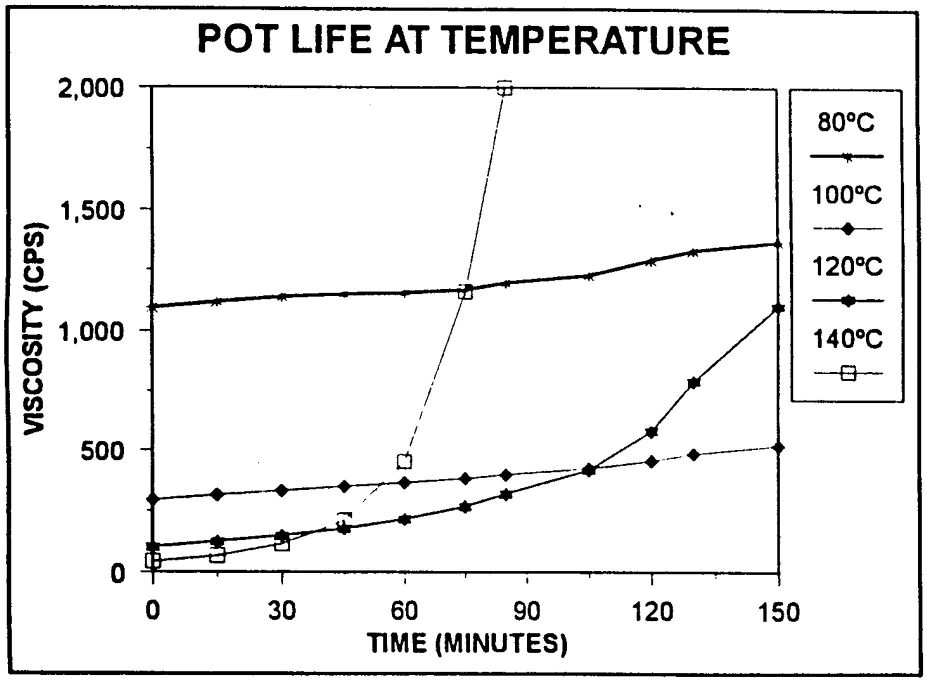
- A stable, one-component paste at room temperature.
(Out-time at room temperature : one month.
Storage temperature: $40^{o}F$)

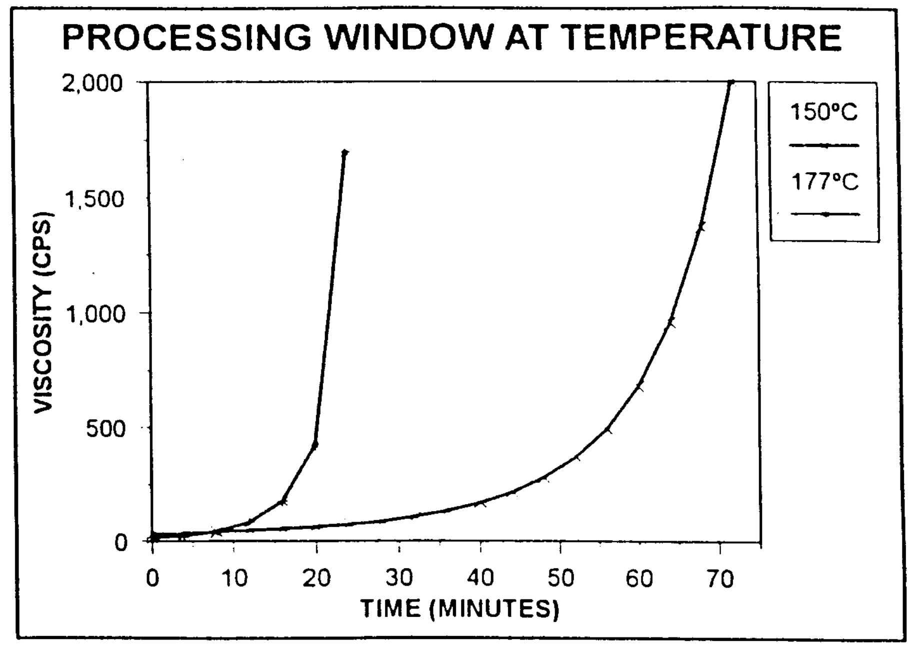
Typical Properties

Visual appearance	Brown paste
Viscosity @ $120^{o}C$	100 cps
Density	1.12 g/cm^3 (9.4 lb/gal)

Resins for RTM

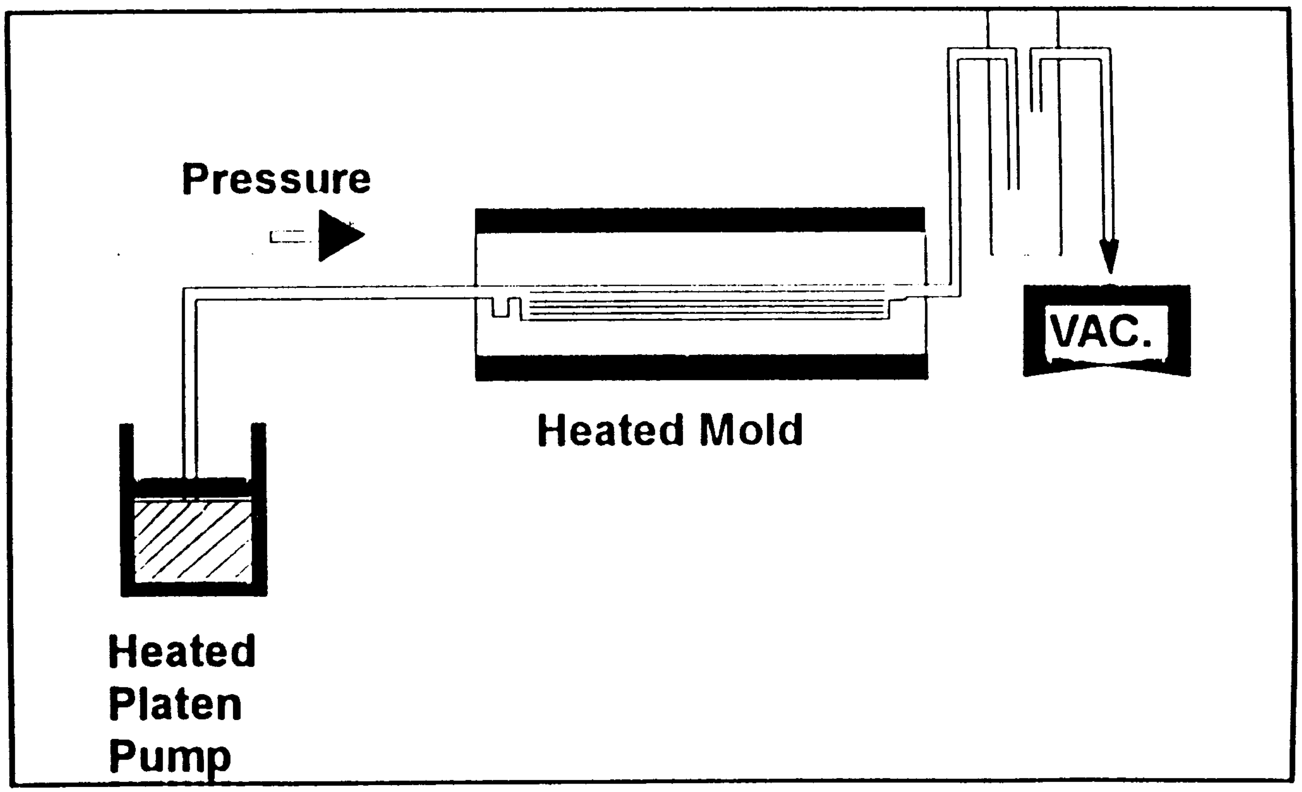
(c) XU MV 723





Resins for RTM

(c) XU MV 723



Resins for RTM

(c) XU MV 723

Composite Properties

Testing Conditions	-54°C (-65°F)	25°C (77°F)	82°C (180°F)	121°C (250°F)
Flexural Strength[1], Ksi (MPa)	116 (800)	125 (860)	120 (830)	105 (725)
Flexural Modulus[1], Msi (GPa)	6.2 (43)	6.9 (48)	6.4 (44)	6.4 (44)
Short Beam Shear [3], Ksi (MPa)		9.4 (65)	9.4 (65)	8.0 (55)
Compressive Strength[6], Ksi (MPa)	123 (850)	125 (860)		
Tensile Strength[5], Ksi (MPa)	63 (435)	78 (540)		
Tensile Modulus, Msi (GPa)	8.6 (59)	8.2 (56)		
Open Hole Compression[10], Ksi (MPa)		48(330)		
Compression After Impact[15] Ksi (MPa)		23(160)		
Glass Transition Temperature				
TMA[7] (°C)	203			
DMA[8] dry (°C)	212			
DMA wet[9] (°C)	203			

Table 7

Testing Conditions	25°C (77°F)	149°C (300°F)	149°C (300°F) Wet[11]	149°C (300°F) Aged[12]
Flexural Strength[1], Ksi (MPa)	125 (860)	87 (600)	43 (300)	98 (675)
Flexural Modulus[1], Msi (GPa)	6.9 (48)	6.1 (42)	3.5 (24)	5.7 (39)
Short Beam Shear [3], Ksi (MPa)	9.4 (65)	6.5 (45)		
Compressive Strength[6], Ksi (MPa)	125 (860)	72 (495)	39 (270)	70 (485)
Tensile Strength[5], Ksi (MPa)	78 (540)	100 (690)	97 (670)	95 (655)
Tensile Modulus, Msi (GPa)	8.2 (56)	8.4 (5.8)	8.3 (5.7)	8.6 (59)

Resins for RTM

(d) 93-104

Features

- One Component Toughened System
- Stable for 1 year at 40^{o}F
- Contains Some Multifunctional Epoxy
- Room Temperature Processible

Resins for RTM

(d) 93-104

Characteristics

Viscosity @ $30^{o}C$ @ $100^{o}C$	11,000 cps 40 cps
Gel Time @ $177^{o}C$	22 minutes
Pot Life @ $100^{o}C$	160 minutes (to 1000 cps)

Resins for RTM

(d) 93-104

Neat Resin Properties (Cured at 177^{o}C for 4 hours)

DMA Tg E'/E", (^{o}C)	161/178
H/W DMA Tg E'/E", (^{o}C).// Water Absorption (%)	129/146//2.6
RT Flexural Str. /Mod./Strain, Ksi/Ksi/%	23.2/527/2.6
180^{o}F WET Flex. Str./Mod./Strain, Ksi/Ksi/%	15.3/398/5.9
RT Tensile Str. /Mod./Elong. Ksi/Ksi/%	13.1/519/3.0
Compression Str./Mod., (ksi/ksi)	33.6/422
G_{1c}, in-lb/in^2 (J/m^2)	2.39 (418)
24hr/82^{o}C Transmission Fluid Soak, DMA E'/E" Tg.(^{o}C)//Absorption, (%)	145/161//0.25

Resins for RTM

(d) 93-104,

Composite Properties

DMA Tg E'/E", (^{o}C)	163/172
Hot/Wet DMA Tg E'/E", (^{o}C)	146/161
Compression Str. (ksi)	112
RT S.B.S. Str., (ksi)	11.4
180^{o}F WET S.B.S. Str., (ksi)	8.4
RT Flex. Str., (ksi)	137
180^{o}F DRY Flex. Str. (ksi)	112
180^{o}F WET Flex. Str. (ksi)	105
Open Hole Compression Str., (ksi)	50
180^{o}F WET OHC Str., (ksi)	41
Compression after Impact Str., (ksi)	34.4

Resins for RTM

(d) 93-104

Summary

- Easy to process
- Unique Toughening Approach
- Good Fracture Toughness and CAI
- Balanced Mechanical Properties up to $180^{o}F$
- Comparably Inexpensive Technology

Resins for RTM

Conclusions

- Four epoxy systems including general purpose, high performance and toughened systems have been reviewed.

- Processing techniques including vacuum, pressure pot and heated platen pump process have been discussed.

Prepreg Technology
A Recent History of Changes in the Industry

Workshop on Closed Mold Manufacturing
15-16 May 1995

Dr. Janet M. Sater
Institute for Defense Analyses

Prepreg Suppliers - Late 1980's

Sources: *Engineered Materials Handbook, Vol. 1, Composites*, ASM International, Ohio, 1987;

Composites: An Insider's Technical Guide to Corporate America's Activities, The Turner Moss Company, New York, 1989

American Cyanamid Co.	
Engineered Materials Division (CA, MD)	various fibers in epoxies, BMIs, PIs
Amoco Corporation	
Amoco Performance Products (SC)	various fibers in epoxies, PAIs
BASF AG (West Germany)	
BASF Structural Materials, Inc.	
BASF Thermoplastic Composites (NC)	various fibers commingled or powder impregnated with PEEK, other TPs, TSs
Narmco Materials Inc. (CA)	various fibers in epoxies, BMIs, phenolics

Prepreg Suppliers - Late 1980's (contd)

British Petroleum Company, plc (England) U.S. Polymeric Inc., (CA) Hitco Materials Division	various fibers in epoxies, BMIs, PIs, etc.
Cape Composites Inc. (CA)	various fibers in PIs (custom)
Ciba Geigy Corporation (Switzerland) Composite Materials (CA)	various fibers in epoxies, BMIs, phenolics
Dexter Corporation, Hysol Aerospace & Industrial Products (CA)	various fibers in epoxies, BMIs, PIs
Dow Chemical Company Composites Technical Service & Development Division (TX)	? fibers in epoxies, etc. (research)

Prepreg Suppliers - Late 1980's (contd)

Ferro Corporation Composites Division (CA)	various fibers in epoxies, BMIs, PIs, phenolics, etc.
Hercules, Inc. Hercules Aerospace Division Bacchus Works (UT)	carbon fibers in epoxies, etc.
Hexcel Corporation Hexcel Livermore Plant (CA)	various fibers in epoxies, BMIs, PIs, phenolics
Hoeschst AG (West Germany) Hoescht Celanese Corporation Polymer Composites, Inc. (MN)	various fibers in PES, PPS, etc.
Imperial Chemical Industries, plc (England) ICI Fiberite Corporation (AZ, TX)	various fibers in epoxies, PEEK, BMIs, PIs, phenolics, etc.

Prepreg Suppliers - Late 1980's (contd)

McCann Manufacturing, Inc. (CT)	various fibers in epoxies
3M Aerospace Materials Department (MN)	various fibers in epoxies
North American Textiles (MI)	carbon fibers commingled with PEEK, etc. (custom)
Park Electrochemical Corp. FiberCote Industries, Inc. (CT)	various fibers in epoxies, phenolics, etc. (custom)
Phillips Petroleum Company, Advanced Composites Division (OK)	various fibers in PAS
Programmed Composites, Inc. (CA)	? fibers in TP and TS resins, (custom)
Quadrax Corporation (RI)	carbon fibers in TP resins, etc.

Prepreg Suppliers - Late 1980's (contd)

Textile Products, Inc. (CA)	various fibers commingled with PEEK, PEI, etc.
Textile Technologies, Inc. (PA)	various fibers commingled with PEEK, PEI, PPS, etc.
Textron, Inc.	
Textron Specialty Materials (MA)	various fibers in epoxies, etc.

Total: 23 companies with facilities in the U.S.

(Note: List limited to companies thought to be producing aerospace grade materials)

Other known major sources:

Toray Industries, Inc., Japan

Prepreg Industry Downsizing

	COMPANY	PLANTS; PRODUCTS	ACTION
4/92	BASF Structural Materials, Inc.	Celion Carbon Fibers Div., Narmco Materials, Thermoplastic Composites; All fiber and prepreg operations	For sale
11/92	British Petroleum	Hitco Materials Division; Prepreg and advanced composites	For sale
9/93	BASF Structural Materials, Inc.	Narmco Materials, Inc.; Prepreg and advanced composites	Sold to American Cyanamid's Cytec Division who becomes 2nd largest prepregger
10/93	American Cyanamid	Engineered Materials Division; advanced composites and prepreg operations	Spun-off Cytec Industries, Cytec Engineered Materials

Prepreg Industry Downsizing (contd)

10/93	Amoco Performance Products	APPI in Greenville, SC; Advanced composites technology and prepreg facilities	Sold to Hexcel Corp., Quadrax Corporation, and ICI Fiberite
12/93	Hexcel Corporation	Various facilities; Honeycomb, resins, fabrics, and advanced composites	In Chapter 11
X/93	Montedison S.p.A.	S.P. Systems, Inc.	For sale
2/95	British Petroleum	Various CA plants including U.S. Polymeric; Prepreg operations	Sold to ICI Fiberite
2/95	Hexcel Corporation	Various facilities; Honeycomb, resins, fabrics, and advanced composites	Emerged from bankruptcy

Prepreg Suppliers - Now

Sources: *Composites: An Insider's Technical Guide to Corporate America's Activities*, The Turner Moss Company, New York, 1994

PM Strategies Critical Business Intelligence on the Key Corporate Players in Performance Materials, Garrett Communications, Inc., 1993

Various issues of *Performance Materials*, August Pacific Press, 1995

Various issues of *High Performance Composites*, Ray Publishing, Inc., 1994-95

Bryte Technologies, Inc. (CA)	various fibers in epoxies, cyanate esters
Cape Composites Incorporated (CA)	carbon and PE fibers in epoxies (custom)
Ciba Composites (CA)	various fibers in epoxies, BMIs, phenolics

Prepreg Suppliers - Now (contd)

Composites, Inc. (CT)	boron/epoxies
Concordia Manufacturing Company, Inc. (RI)	carbon fiber commingled with PEEK, PPS
Cytec Industries	
Cytec Engineered Materials (CA) (Spin-off from American Cyanamid)	various fibers in epoxies, BMIs, phenolics
Park Electrochemical Corporation	
FiberCote Industries, Inc. (CT)	various fibers in PS, PES, PEI (custom), etc.
GEC-Marconi (England)	
GEC-Marconi Materials Corporation (CA)	various fibers in epoxies, phenolics, PIs, etc.
B.F. Goodrich Company	
B.F. Goodrich Adhesive Systems Division (OH)	various fibers in epoxies, phenolics

Prepreg Suppliers - Now (contd)

Hercules Incorporated	
Hercules Advanced Materials & Systems Company	
Composite Products Group (UT)	carbon fibers in various resins
Hexcel Corporation	
Plants in AZ, CA	various fibers in epoxies, BMIs, PIs, phenolics, etc.
HyComp, Inc. (OH)	various fibers in PIs (custom)
Imperial Chemical Industries plc (England)	
ICI Fiberite (AZ, TX)	various fibers in epoxies, cyanate esters, PEEK, BMIs, PIs, phenolics
3M	
Aerospace Industrial Tapes & Specialties (MN)	various fibers in epoxies

Prepreg Suppliers - Now (contd)

Newport Adhesives and Composites, Inc. (CA)	various fibers in various resins (custom)
North American Textiles (MI)	carbon fiber commingled with PEEK, etc.
Programmed Composites, Inc. (CA)	carbon fibers in epoxies, cyanate esters (custom)
Quadrax Corporation (RI)	various fibers in PEIs, PEEK, PPS, other thermoplastics
Montedison S.p.A. (Italy)	
S.P. Systems Inc., Composites Division (CA)	various fibers in epoxies, PIs, phenolics, etc.
Textile Products Inc. (CA)	various fibers commingled with PEEK, etc.

Prepreg Suppliers - Now (contd)

Mutual Industries North, Inc.	
Textile Technologies Industries, Inc. (PA)	various fibers commingled with PEEK, PEI, etc.
Toray Industries, Inc. (Japan)	
Toray (WA)	carbon fibers in epoxies
YLA, Incorporated (CA)	various fibers in cyanate esters, etc.

Total: 23 companies with facilities in the U.S.

(Note: List limited to companies thought to be producing aerospace grade materials)

Composite Material Suppliers - Issues

Flux in the advanced composites industry

- i.e., Mergers, sell-outs, dropped product lines, plant closings

Small to non-existent aerospace markets

High processing costs

- Tooling, fabrication, assembly

Prepreg Suppliers - Issues

U.S. carbon fiber sources for aerospace applications

Amoco (PAN, pitch), Hercules (PAN)

Production of aerospace-grade prepreg materials limited primarily to a few companies

Top 3 (U.S.): ICI Fiberite, Cytec, Hexcel

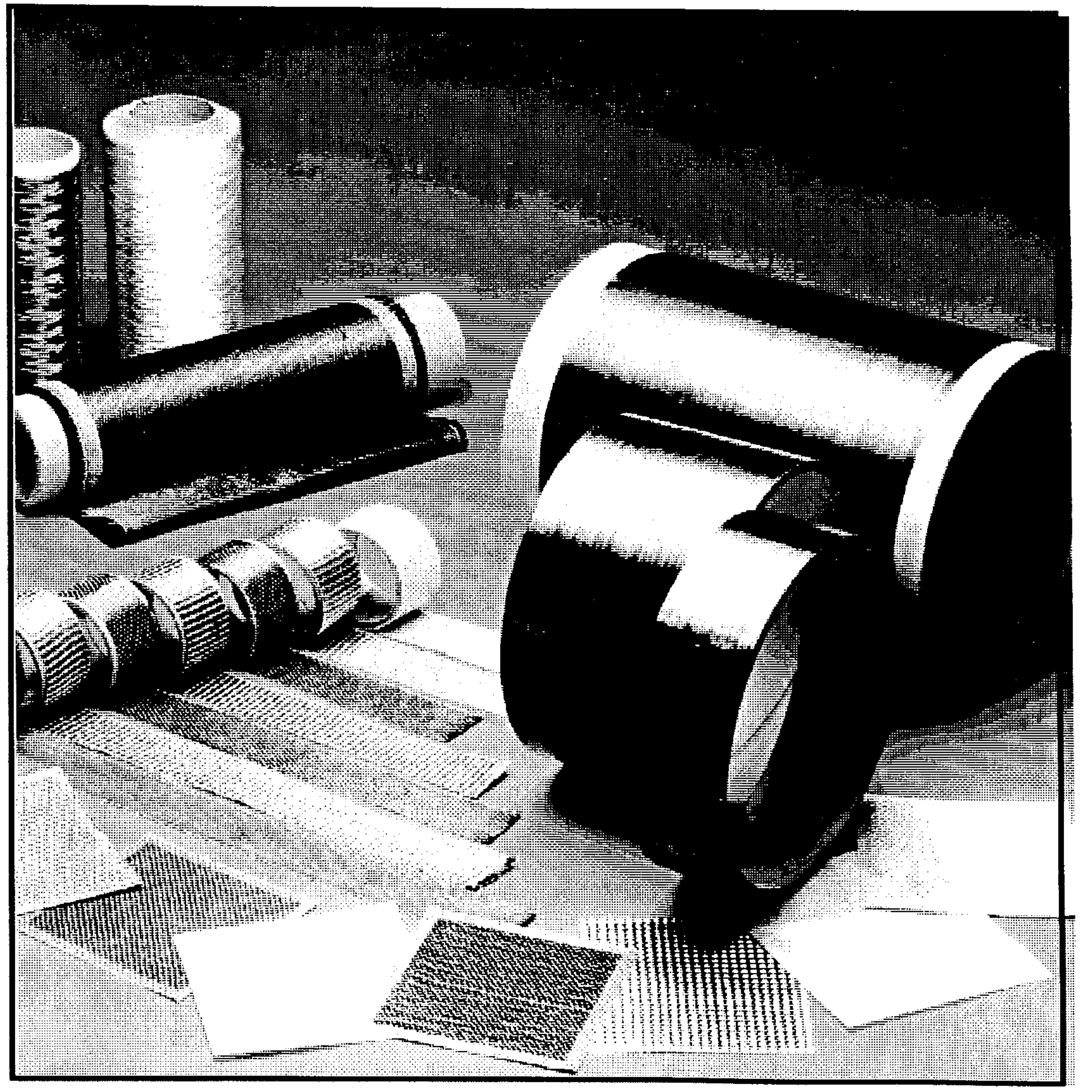
Overcapacity

Foreign competition

Multiple and variable quality standards and certification requirements

ICI FIBERITE

THERMOSET COMPOSITE MATERIALS



ICI Thermoset Resins

- Epoxy
- Toughened Epoxy
- Cyanate Ester
- Bismaleimide
- Polyimide
- Others
  - Phenolic
  - Polyester

Thermoset Resins

EPOXY (350°F CURING)

- 934 Resin: Aircraft laminate and sandwich panel structures; spacecraft structures.
- 937A Resin: Licensed Hercules 3501-6 formulation; aircraft and spacecraft laminate and sandwich panel structures
- 938 Resin: Aircraft laminate and sandwich panel structures; spacecraft structures
- 976 Resin: Aircraft laminate and sandwich panel structures.
- 984 Resin: Aircraft laminate and sandwich panel structures; formable into thick sections

ICI FIBERITE

D91-014/0514-7

Thermoset Resins

TOUGHENED EPOXY (350°F)

- 977 Resins: Second generation toughened epoxy family; each is a thermoset / thermoplastic blend with varying degrees of toughness and compressive properties. Includes 977-1, 977-2, and 977-3

ICI FIBERITE

D91-014/0514-10

Thermoset Resins

CYANATE ESTER (350°F CURING)

- 954 Resins: A group of resins cured via an addition mechanism results in glass transition temperatures of 330-500°F.
- 954-2A: Toughened system for primary structural aircraft parts.
- 954-3: Space applications; excellent microcrack, radiation resistance and low moisture absorption.

ICI FIBERITE

D91-014/0514-25

Thermoset Resins

BISMALEIMIDE (370°F CURING)

- 986 Resin: Structural aircraft parts subjected to high temperatures with 370°F cure and 470°F post cure. Dry service temperature is 425°F and wet service temperature is 325°F.

FIBERITE

D91-014/0514-22

Thermoset Resins

POLYIMIDE (350°F TO 600°F CURING)

- 944 Resin: Skybond 703 condensation polyimide; high temperature missile applications

- 966C Resin: Licensed NASA PMR-15; aircraft engines and other high temperature applications

ICI FIBERITE

D91-014/0514-19

Reinforcements

- Carbon
- Fiberglass (E & S-2)
- Aramid (Kevlar®)
- Quartz

ICI FIBERITE

D91-014/0514-26

Reinforcements

CARBON FIBER

- Most common and versatile class of reinforcement today
- Produced from either PAN or pitch precursor
- A broad range of strength, modulus and strain combinations possible
- Carbon fiber can be classified in four different performance groups depending on tensile modulus, strength or precursor type:
  - standard modulus
  - intermediate modulus
  - high modulus
  - pitch fibers

ICI FIBERITE

D91-014/0514-27

ICI Pilot Plant, Tempe, AZ
Solution Prepregging

Solution Treater		
Three zones		
Width	36 inches	
Temperature	$\leq 600^{o}F$	
Product limitations		
Fabrics (width)		$\leq$34 inches
FX products		4 tows
String molding compounds		
Mat products (width)		$\leq$34 inches
Drum Winder		
Width	$\leq$12 inches	
Length	72 inches	

ICI Pilot Plant, Tempe, AZ
Unitape Production Capabilities

Fiber Areal Weight*	30 to 380 gm/m^2
Resin Areal Weight	21 to 400 gm/m^2
Tape Width	1 to 24 inches

Able to use several different papers

Able to film highly filled resin systems

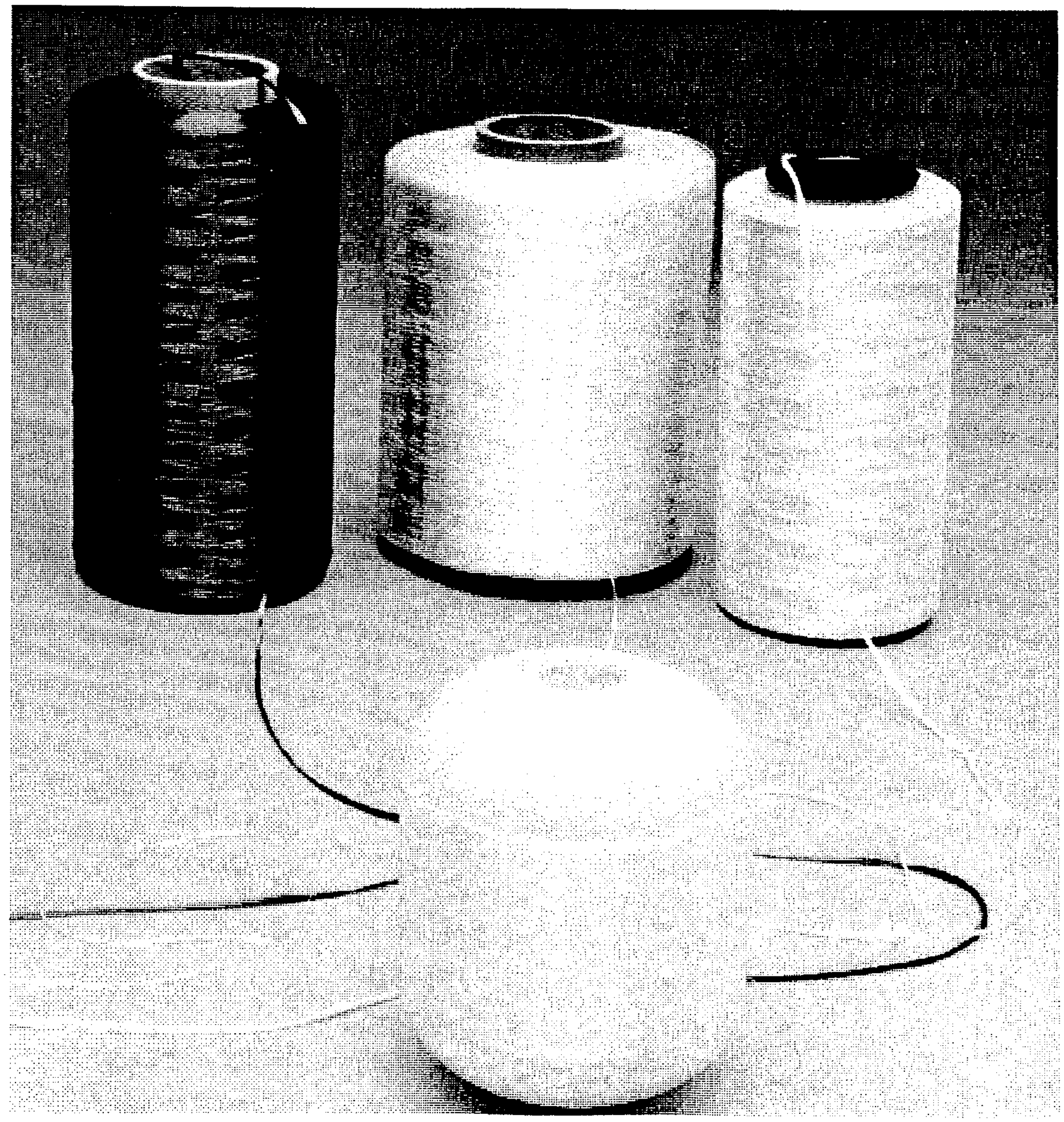
Capable of filming pseudo hot melts

*Low FAWs typically require higher RC ranges and small tow sizes.

Product Forms

ROVING

- Single- or multiple bundles of fibers which are coated with resin and wound on spools



Product Forms

WOVEN FABRIC

- Unidirectional: Up to 95% of fibers are oriented in the 0° direction
- Bidirectional
  - 0/90°: Standard bidirectional weave
  - ±45° : Yarns are interwoven at ±45° angles.
- Hybrid: Uses a mixture of two or more different types of yarn (carbon/fiberglass or carbon/Kevlar® combinations)
- Non-Crimp: Heavier fibers are interwoven with lighter carrier fibers
- Stitched Multi-Layered Fabrics: Created by stitching bidirectional fabrics with ±45° fabrics.

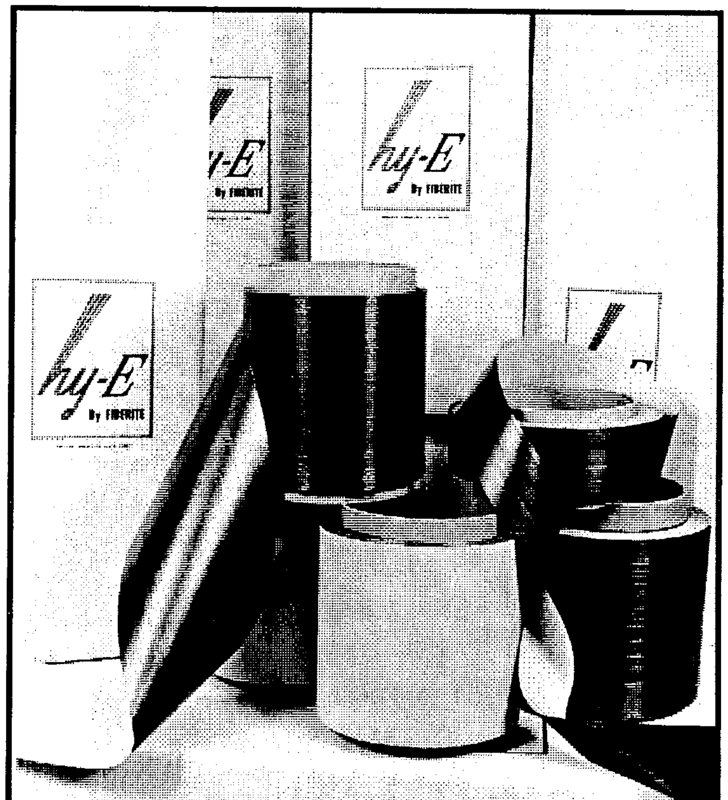
ICI FIBERITE

D91-014/0514-33

Product Forms

UNIDIRECTIONAL TAPE

- High modulus tape made from numerous tows of fiber all running in the same direction. The tows are impregnated with resin as the tape is made.



ICI FIBERITE

D91-014/0514-32

Typical Quality Control Methods

Material Form	Property	Test Method
Uncured resin	Composition	High Performance Liquid Chromatography (HPLC) InfraRed Spectrosocopy (IRS) Gel Permeation Chromatography (GPC) Differential Scanning Calorimetry (DSC)
	Processability	Rheometric Dynamic Scanning (RDS) Viscosity Gel time Volatile content
	Others	Resin film thickness Resin film areal weight
Reinforcement form (fibers, fabrics, etc.)	Processability	Tow yield Tow count Fiber density Fiber areal weight Volume

Typical Quality Control Methods (contd)

Material Form	Property	Test Method
Cured resin	Completeness of cure	T_g
	H_2O/solvent resistance	T_g (wet) Moisture weight gain Solvent weight gain
	Resin toughness	Cleavage (G_{1C})
	Others	Density

Typical Quality Control Methods (contd)

Material Form	Property	Test Method
Uncured impregnated system	Characterization	HPLC IRS DSC
	Processability	Resin Content (RC) Fiber volume fraction Flow, RDS viscosity Gel time Volatiles Tack, drape
	Others	Prepreg density Thickness per ply Process yield

Typical Quality Control Methods (contd)

Material Form	Property	Test Method
Cured impregnated system	Completeness of cure	T_g DSC
	Moisture resistance	Weight gain
	Thermal properties	Thermal conductivity CTE Specific heat
	Laminate properties	Ply thickness Fiber volume fraction Specific gravity, density Various mechanical properties
	Electrical properties (optional)	Dielectric constant Dielectric strength Dissipation factor Volume resistivity

Data Sheet on

977-1 Prepreg Material

from the

ICI FIBERITE

MATERIAL HANDBOOK

A Data Sheet from

ICI FIBERITE

977-1 EPOXY RESIN

- Toughened epoxy using ICI Fiberite's proprietary "co-continuous" morphology
- Outstanding impact resistance
- Available in a broad range of fibers and forms including tape, fabric and roving
- 350°F (177°C) cure
- Controlled flow
- Tack suitable for ATL or hand lay-up
- 220°F (104°C) dry and 180°F (82°C) wet service temperature
- Autoclave or press-mold processing
- Shelf life
  6 months at 0°F (-18°C)
  42 days at 70°F (21°C)

Fiberite® 977-1 is a 350°F (177°C) curing, highly-toughened epoxy resin with a 220°F (104°C) dry and 180°F (82°C) wet service capability. Fiberite 977-1 is formulated for autoclave or press molding. Unidirectional tape and woven fabric impregnated with 977-1 resin will retain tack for several days at 70°F (21°C) and has a long mechanical outlife suitable for fabrication of large structures.

The recommended lay-up procedure for this material is L-3. The recommended cure procedure is C-5.

Typical applications for 977-1 include primary and secondary commercial aircraft structure or any application where high impact resistance, good mechanical properties, and light weight are required.

March 1, 1995 (Rev. E)

A Data Sheet from

ICI FIBERITE

TYPICAL PROPERTIES OF FIBERITE 977-1 COMPOSITE LAMINATES

INTERMEDIATE MODULUS (40 Msi/276 GPa CLASS) HERCULES IM-7 CARBON FIBER REINFORCED UNIDIRECTIONAL TAPE

Fiberite Product Codes
Hy-E 1377-1T
Hy-E 5377-1A

Mechanical Properties	-75°F (-60°C)	RT	180°F (82°C)	180°F WET[1] (82°C WET[1])	180°F SOLV'T (82°C SOLV'T)
0° Tensile Properties					
Strength, ksi (MPa)	365 (2520)	370 (2550)			
Modulus, Msi (GPa)	22.0 (150)	21.6 (150)			
0° Compressive Properties					
Strength, ksi (MPa)		230(1590)	207 (1430)	178 (1080)	
Modulus, Msi (GPa)	20.5 (140)	20.1 (140)			
Compression After Impact 270 in-lb. (30.5 J) Impact Level, ksi (MPa)		48.4 (330)			
Comp. Interlaminar Shear, ksi (MPa)		12.7 (88)	10.0 (69)	8.0 (55)	
Open Hole Tensile[2], ksi (MPa)	65.6 (452)	64.2 (443)			
Open Hole Compression[3], ksi (MPa)		46.5 (321)	40.4 (279)	37.6 (259)	
Open Hole Compression[3], ksi (MPa)					
MEK[4]					38.6 (266)
Jet A[4]					38.2 (263)
De-icing Fluid[4]					38.6 (266)
Skydrol[5]					37.8 (261)
Double Cantilever Beam (G_{IC}) in-lbs/in² (J/m²)		2.07 (363)			

All above data was generated using 190 g/m² material. Laminates were between 56-60% fiber volume. All testing per BMS 8-276. Cure = 2 hours at 355°F, 85 psi.

[1]Wet Condition = 14-day immersion in 160°F water
[2]$(+45,0,-45,90)_S$ lay-up
[3]$(+45,0,-45,90)_{2S}$ lay-up
[4]Tested after 14-day room temperature immersion
[5]Tested after 14-day 160°F immersion

The data listed has been obtained from carefully controlled samples considered to be representative of the product described. Because the properties of this product can be significantly affected by the fabrication and testing techniques employed and since ICI Fiberite does not control the conditions under which its products are tested and used, ICI Fiberite cannot guarantee that the properties listed will be obtained with other processes and equipment.

A Data Sheet from

FIBERITE

TYPICAL PROPERTIES OF FIBERITE 977-1 COMPOSITE LAMINATES

INTERMEDIATE MODULUS (40 Msi/276 GPa CLASS) CELION G40-800 CARBON FIBER REINFORCED UNIDIRECTIONAL TAPE

Fiberite Product Code
Hy-E 1577-1E

Mechanical Properties	-75°F (-60°C)	RT	180°F (82°C)	180°F WET[1] (82°C WET[1])
0° Tensile Properties				
Strength, ksi (MPa)	449 (3100)	427 (2940)		
Modulus, Msi (GPa)	22.0 (150)	22.0 (150)		
Strain, %	1.89	1.79		
0° Compressive Properties				
Strength, ksi (MPa)		232 (1600)	201 (1390)	196 (1350)
Modulus, Msi (GPa)	20.4 (140)	20.3 (140)		
Compression After Impact 270 in-lb. (30.5 J) Impact Level, ksi (MPa)		49.4 (341)		
Comp. Interlaminar Shear, ksi (MPa)		12.9 (89)	10.1 (69.6)	8.8 (61)
Open Hole Tensile[2], ksi (MPa)	65.8 (454)	65.0 (448)		
Open Hole Compression[3], ksi (MPa)		44.2 (303)	38.1 (262)	35.0 (241)
Double Cantilever Beam (G_{IC}) in-lbs/in² (J/m²)		3.24 (568)		

All above data was generated using 190 g/m² material. Laminates were between 56-60% fiber volume. All testing per BMS 8-276. Cure = 2 hours at 350°F, 85 psi.

[1]Wet Condition = 14-day immersion in 160°F water
[2]$(+45,0,-45,90)_S$ lay-up
[3]$(+45,0,-45,90)_{2S}$ lay-up

A Data Sheet from

ICI FIBERITE

977-1 EPOXY RESIN

PRODUCT SAFETY

Material Safety Data Sheets for ICI Fiberite products can be obtained from the ICI Fiberite Safety, Health and Environmental Affairs Department in Winona, Minn. by calling (507) 452-8051.

PRODUCT HANDLING

The wearing of clean, impervious gloves is recommended when working with prepreg materials. See Material Safety Data Sheet for more information.

SHIPPING

Prepreg is typically shipped as rolls in sealed aluminum or polyethylene bags in cardboard containers packed with dry ice.

DISPOSAL OF SCRAP MATERIAL

Disposal of material should be in accordance with local, state, and federal regulations, which may vary by location. Questions concerning disposal should be directed to the ICI Fiberite Safety, Health, and Environmental Affairs Department in Winona, Minn. for evaluation on a case-by-case basis.

Data Sheet on

977-2 Prepreg Material

from the

ICI FIBERITE

MATERIAL HANDBOOK

A Data Sheet from

FIBERITE

977-2 EPOXY RESIN

- Toughened epoxy using ICI Fiberite's proprietary "co-continuous" morphology
- 350°F (177°C) cure
- Available in a broad range of fibers and forms including tape, fabric and roving
- Excellent impact resistance
- Controlled flow
- 260-280°F (126-138°C) dry and 220°F (104°C) wet service temperature
- Autoclave or press-mold processing
- Shelf life
  12 months at 0°F (-18°C)
  42 days at 70°F (21°C)

Fiberite® 977-2 is a 350°F (177°C) curing toughened epoxy resin with a 260-280°F (126-138°C) dry and 220°F (104°C) wet service capability. Fiberite 977-2 is formulated for autoclave or press molding. Unidirectional tape and woven fabric impregnated with 977-2 resin will retain tack for at least 10 days at 70°F (21°C) and has a long mechanical outlife suitable for fabrication of large structures.

The recommended lay-up procedure for this material is L-15. The recommended cure procedure is C-50.

Typical applications for 977-2 include aircraft primary and secondary structure, space structure, ballistics, cryogenic tanks, or any application where impact resistance and light weight are required.

TYPICAL NEAT RESIN PROPERTIES

	RT
Tensile Strength, ksi	11.8 ± 1.6
Tensile Modulus, Msi	0.51 ± 0.02
Tensile Strength, MPa	*81.4 ± 11*
Tensile Modulus, GPa	*3.52 ± 0.14*
Flexural Strength, ksi	28.6 ± 1.0
Flexural Modulus, Msi	0.50 ± 0.01
Flexural Strength, MPa	*197 ± 7*
Flexural Modulus, GPa	*3.45 ± 0.07*
G_{1c}	
in-lb/in²	2.73 ± 0.48
J/m²	478 ± 84
K_{1c}	
MPa • m$^{1/2}$	1.34 ± 0.15
ksi • in.$^{1/2}$	1.22 ± 0.14
Tg, °C (RDS, 10°C/min)	212
Density, g/cc	1.31

The data listed has been obtained from carefully controlled samples considered to be representative of the product described. Because the properties of this product can be significantly affected by the fabrication and testing techniques employed and since ICI Fiberite does not control the conditions under which its products are tested and used, ICI Fiberite cannot guarantee that the properties listed will be obtained with other processes and equipment.

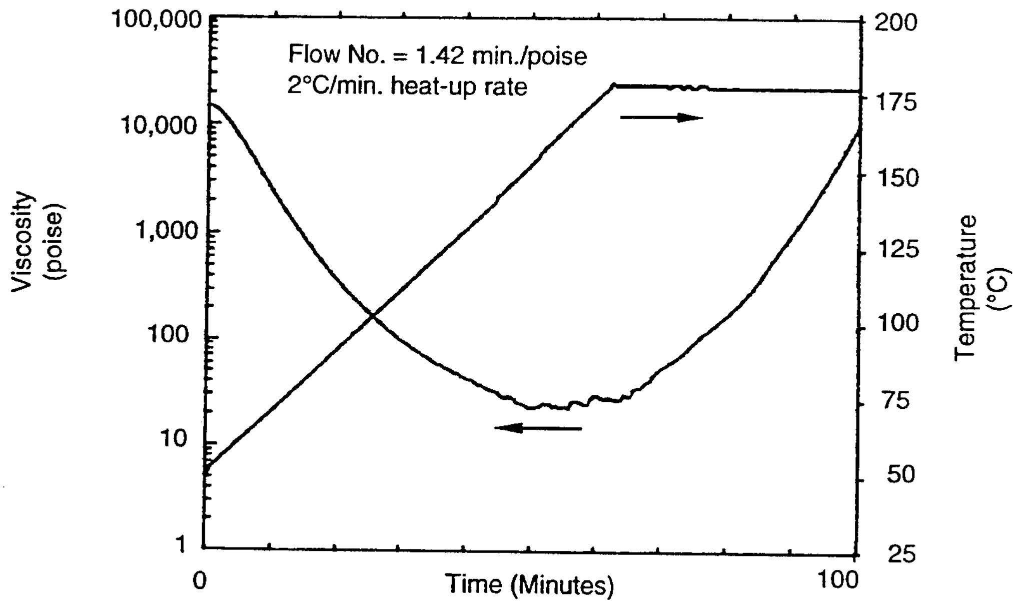
A Data Sheet from

ICI FIBERITE

977-2 EPOXY RESIN

977-2 VISCOSITY PROFILE

Straight Heat-Up Cure Cycle to 350°F (177°C)



The data listed has been obtained from carefully controlled samples considered to be representative of the product described. Because the properties of this product can be significantly affected by the fabrication and testing techniques employed and since ICI Fiberite does not control the conditions under which its products are tested and used, ICI Fiberite cannot guarantee that the properties listed will be obtained with other processes and equipment.

A Data Sheet from

ICI FIBERITE

TYPICAL PROPERTIES OF FIBERITE 977-2 COMPOSITE LAMINATES

INTERMEDIATE MODULUS (40 Msi/276 GPa CLASS) CARBON FIBER REINFORCED UNIDIRECTIONAL TAPE

Typical Fiberite Product Code
Hy-E 1377-2T
Hy-E 1577-2E
Hy-E 5377-2A

Mechanical Properties	**-65°F (-54°C)**	**RT**	**180°F (82°C)**	**180°F WET (82°C WET)**
0° Tensile Properties				
Strength, ksi	390	390	–	–
Modulus, Msi	24.0	24.0	–	–
Strength, MPa	*2690*	*2690*	–	–
Modulus, GPa	*165*	*165*	–	–
0° Compressive Properties				
Strength, ksi	–	230	210	180
Modulus, Msi	–	22.0	22.0	22.0
Strength, MPa	–	*1580*	*1450*	*1240*
Modulus, GPa	–	*152*	*152*	*152*
Quasi Compression After 1500 in-lb/in Impact				
Strength, ksi	–	38	–	–
Strength, MPa	–	*262*	–	–
Quasi Open Hole Compression				
Strength, ksi	–	45	39	37
Strength, MPa	–	*310*	*269*	*255*
Quasi Open Hole Tensile				
Strength, ksi	–	65	–	–
Strength, MPa	–	*448*	–	–

Property values listed are typical for laminates with 57 to 63% fiber volume. All testing per BMS 8-276.
Cure = 3 hours at 355°F (180°C).
Wet = 7 day water immersion @ 165°F (74°C).

A Data Sheet from

FIBERITE

977-2 EPOXY RESIN

PRODUCT SAFETY

Material Safety Data Sheets for ICI Fiberite products can be obtained from the ICI Fiberite Safety, Health and Environmental Affairs Department in Winona, Minn. by calling (507) 454-3611.

PRODUCT HANDLING

The wearing of clean, impervious gloves is recommended when working with prepreg materials. See Material Safety Data Sheet for more information.

SHIPPING

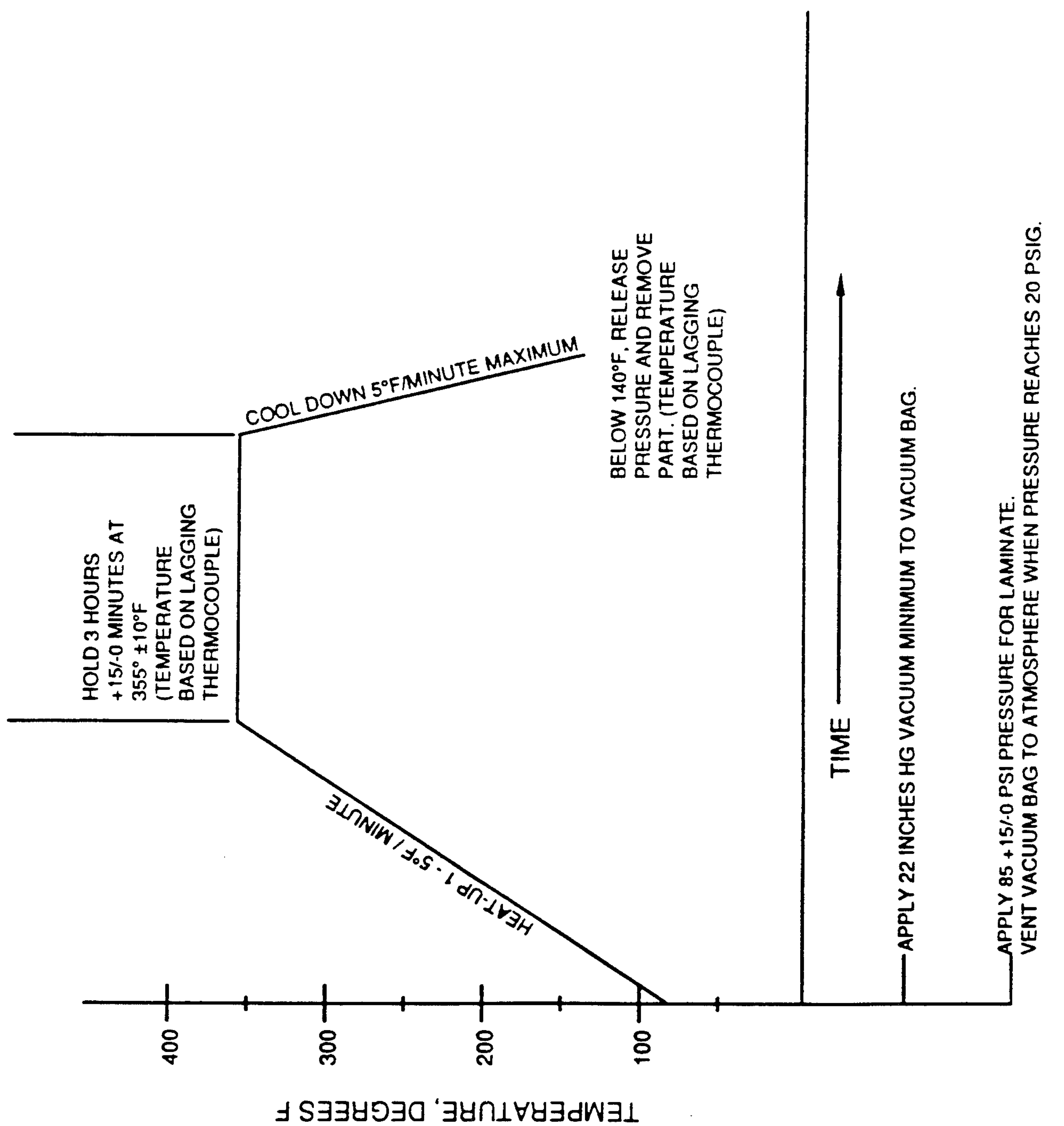
Prepreg is typically shipped as rolls in sealed aluminum or polyethylene bags in cardboard containers packed with dry ice.

DISPOSAL OF SCRAP MATERIAL

Disposal of material should be in accordance with local, state, and federal regulations, which may vary by location. Questions concerning disposal should be directed to the ICI Fiberite Safety, Health, and Environmental Affairs Department in Winona, Minn. for evaluation on a case-by-case basis.

FIBERITE®

CURE CYCLE C-50



Data Sheet on

977-3 Prepreg Material

from the

ICI FIBERITE

MATERIAL HANDBOOK

A Data Sheet from

ICI **FIBERITE**

977-3 EPOXY RESIN

- Toughened epoxy using ICI Fiberite's proprietary "co-continuous" morphology
- Superior hot/wet performance with impact resistance
- 350°F (177°C) cure
- Available in a broad range of fibers and forms including tape, fabric and roving
- 350°F (177°C) dry and 270°F (132°C) wet service temperature
- Autoclave or press-mold processing
- Shelf life
  6 months at 0°F (-18°C)
  30 days at 70°F (21°C)

Fiberite® 977-3 is a 350°F (177°C) curing toughened epoxy resin with a 350°F (177°C) dry and 270°F (132°C) wet service capability. Fiberite 977-3 is formulated for autoclave or press molding and can be cured at 350°F for six hours. The recommended lay-up procedure for this material is L-15. The recommended cure procedure is C-49.

Unidirectional tape and woven fabric impregnated with 977-3 resin will retain tack for 30 days at 70°F (21°C) and has a long mechanical outlife suitable for fabrication of large structures.

Typical applications for 977-3 include aircraft primary and secondary structure or any application where impact resistance and excellent hot/wet performance are crucial.

CURED(1) NEAT RESIN PROPERTIES

	RT	250°F/Wet(2) (121°C/Wet(2))
Compressive Yield Strength, ksi *Compressive Yield Strength, MPa*	27.0 ± 0.3 *186 ± 2.1*	
Flexural Strength, ksi Flexural Modulus, Msi	21.0 ± 4.4 0.55 ± 0.01	10.1 ± 0.4 0.35 ± 0.3
Flexural Strength, MPa *Flexural Modulus, GPa*	*144.7 ± 30.3* *3.79 ± 0.07*	*69.6 ± 2.8* *2.41 ± 2.1*
K_{1C}, MPa • $m^{1/2}$ G_{1C}, J/m^2	0.90 ± 0.08 217 ± 24	
RDS DMA Tg, °C (tested @ 5°C/min)		
	G'	178, 218
	G"	189, 226
	Tan Delta	190, 240

(1)Cured at 355°F (180°C) for 6 hours.
(2)Wet = 7-day water immersion at 160°F (71°C)
(3)Flexural testing performed using a 3-point loading fixture and a 16:1 S/D ratio
(4)K_{1C} and G_{1C} tested using 3-point bending mode.

A Data Sheet from

ICI FIBERITE

TYPICAL PROPERTIES OF FIBERITE 977-3 COMPOSITE LAMINATES

INTERMEDIATE MODULUS (40 Msi/276 GPa CLASS) CARBON FIBER REINFORCED UNIDIRECTIONAL TAPE

Typical Fiberite Product Code
Hy-E 1377-3T
Hy-E 5377-3A
Hy-E 1577-3E

Mechanical Properties	-75°F	RT	220°F		250°F		270°F		300°F	
			Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet
0° Tensile Properties										
Strength, ksi	353	364								
Modulus, Msi	22.9	23.5								
Strain, %	1.52	1.46								
90° Tensile Properties										
Strength, ksi		9.3								
Modulus, Msi		1.21								
Strain, %		0.77								
0° Compressive Properties										
Strength, ksi		244		221[1]		195[1]		180[1]		160[1]
Modulus, Msi		22.3	21.4	21.2[1]	20.4	21.2[1]	20.2	22.6[1]	21.5	21.7[1]
Open Hole Compression										
Strength, ksi (25/50/25 orientation)		46.7		37.0[2]		35.0[2]				
0° Interlaminar Shear Properties										
Strength, ksi		18.5	13.6	12.9[1]	13.3	11.4[1]	12.4	10.1[1]	11.4	9.0[1]
In-Plane Shear Properties (±45)										
Modulus, Msi Weight Gain = 0.9%		0.72		0.61[3]		0.58[3]		0.50[3]		0.34[3]
0° Flexural Properties										
Strength, ksi		256	246	173[1]	221	162[1]	218	140[1]	206	125[1]
Modulus, Msi		21.7	22.2	20.1[1]	20.8	21.2[1]	21.0	19.6	21.0	18.9
90° Flexural Properties										
Strength, ksi		19.0								
Modulus, Msi		1.19								
Edge Delamination Strength, ksi										
Onset		37								
Ultimate		92								
Compression After Impact, ksi (25/50/25 orientation 270 in-lb impact level)		28								
Interlaminar Fracture Toughness										
G_{Ic} (DCB), in-lb/in		1.8								
G_{IIc} (ENF), in-lb/in		3.3								

NOTES: All panels cured for 6 hours at 355°F, 85 psi
[1]Wet = 1 week immersion in 160°F water
[2]Wet = 2 week immersion in 160°F water
[3]Wet = 150°F/85% RH to equilibrium (approximately 1.1% weight gain)

A Data Sheet from

ICI FIBERITE

TYPICAL PROPERTIES OF FIBERITE 977-3 COMPOSITE LAMINATES

INTERMEDIATE MODULUS (40 Msi/276 GPa CLASS) HERCULES IM-7 CARBON FIBER REINFORCED UNIDIRECTIONAL TAPE

Typical Fiberite Product Code
Hy-E 1377-3T
Hy-E 5377-3A

Mechanical Properties	-60°C	RT	104°C		121°C		132°C		149°C	
			Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet
0° Tensile Properties										
Strength, MPa	2430	2510								
Modulus, GPa	158	162								
Strain, %	1.52	1.46								
90° Tensile Properties										
Strength, MPa		64.1								
Modulus, GPa		8.34								
Strain, %		0.77								
0° Compressive Properties										
Strength, MPa		1680		1520[1]		1340[1]		1240[1]		1100[1]
Modulus, GPa		154	147	146[1]	141	146[1]	139	156[1]	148	150[1]
Open Hole Compression										
Strength, MPa (25/50/25 orientation)		322		225[2]		241[2]	--			
0° Interlaminar Shear Properties										
Strength, MPa		127	93.6	88.9[1]	91.7	78.6[1]	85.5	69.6[1]	78.6	62[1]
In-Plane Shear Properties										
Modulus, GPa (±45) Weight Gain = 0.9%		4.96		4.21[3]		4.00[3]		3.45[3]		2.34[3]
0° Flexural Properties										
Strength, MPa		1765	1700	1200[1]	1524	1120[1]	1500	965[1]	1420	862[1]
Modulus, GPa		150	153	139[1]	143	146[1]	145	135	145	130
90° Flexural Properties										
Strength, MPa		131								
Modulus, GPa		8.20								
Edge Delamination Strength, MPa										
Onset		255								
Ultimate		634								
Compression After Impact, MPa (25/50/25 orientation 270 in-lb impact level)		193								
Interlaminar Fracture Toughness										
G_{IC} (DCB), in-lb/in		1.8								
G_{IIC} (ENF), in-lb/in		3.3								

NOTES: All panels cured for 6 hours at 177°C, 0.586 MPa
[1]Wet = 1 week immersion in 71°C water
[2]Wet = 2 week immersion in 71°C water
[3]Wet = 66°C/85% RH to equilibrium (approximately 1.1% weight gain)

977-3 EPOXY RESIN

PRODUCT SAFETY

Material Safety Data Sheets for ICI Fiberite products can be obtained from the ICI Fiberite Safety, Health and Environmental Affairs Department in Winona, Minn. by calling (507) 452-8051.

PRODUCT HANDLING

The wearing of clean, impervious gloves is recommended when working with prepreg materials. See Material Safety Data Sheet for more information.

SHIPPING

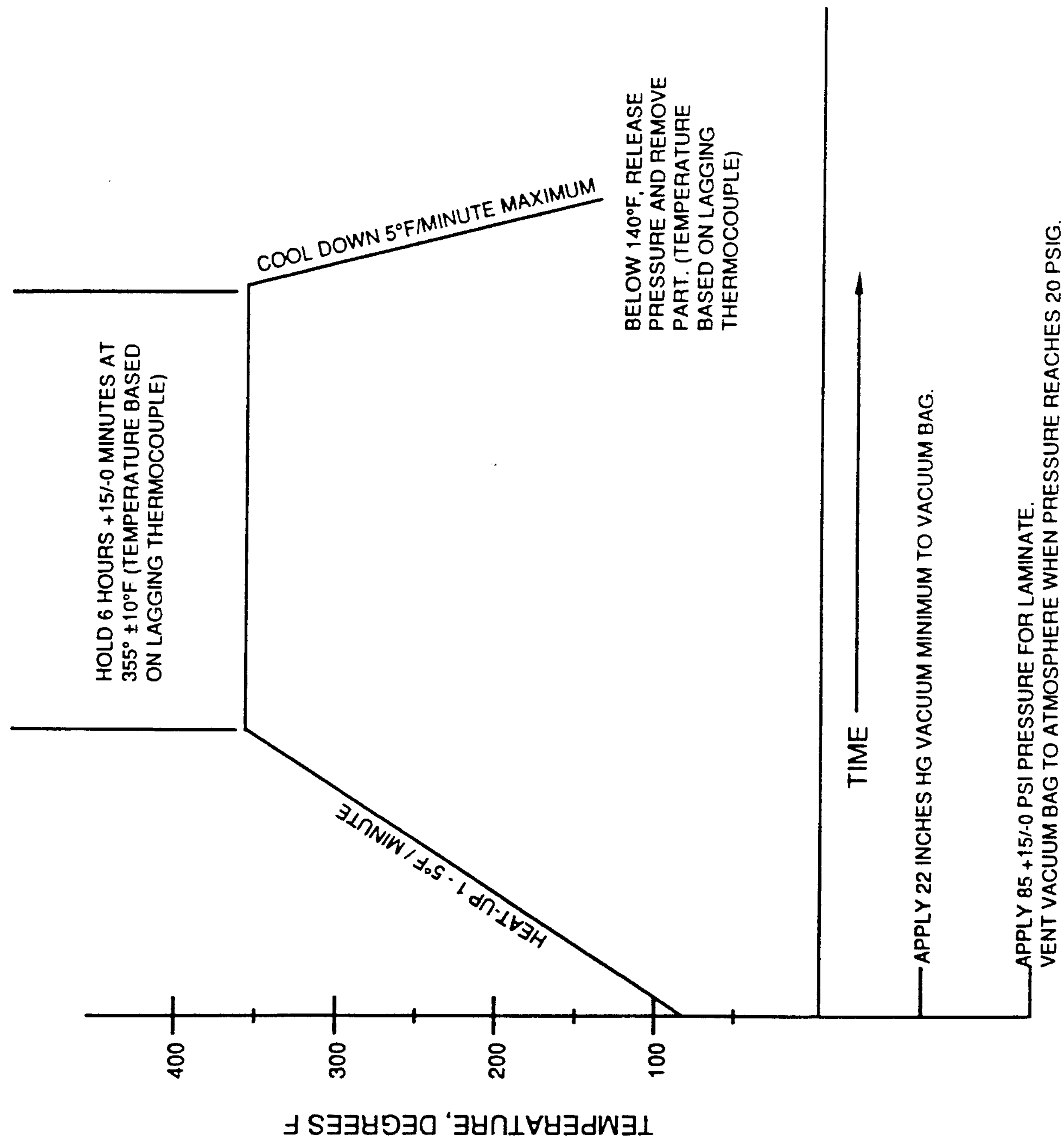
Prepreg is typically shipped as rolls in sealed aluminum or polyethylene bags in cardboard containers packed with dry ice.

DISPOSAL OF SCRAP MATERIAL

Disposal of material should be in accordance with local, state, and federal regulations, which may vary by location. Questions concerning disposal should be directed to the ICI Fiberite Safety, Health, and Environmental Affairs Department in Winona, Minn. for evaluation on a case-by-case basis.

FIBERITE

CURE CYCLE C-49



A Data Sheet from

FIBERITE

954-2A CYANATE RESIN

- Toughened cyanate using ICI Fiberite's proprietary thermoplastic technology
- High impact resistance
- 325°F (163°C) wet service temperature with post cure
- Attractive electrical properties
- 350°F (177°C) cure
- Controlled flow, good tack and out-life
- Available on a broad range of fibers and in forms including tape and fabric
- Autoclave or press-mold processable

Fiberite® 954-2A is a 350°F (177°C) curing toughened cyanate resin with a 325°F (163°C) wet service capability. Fiberite 954-2A is formulated for autoclave or press molding. Recommended cure is four hours at 350°F (177°C). Service temperatures are maximized by a post cure of 428°F - 450°F (220°C - 232°C). The recommended lay-up procedure for this material is L-7. The recommended cure procedure is C-33. The hold at 250°F (121°C) may be omitted, if desired.

Typical applications for 954-2A include primary and secondary aircraft structures, space structures, cryogenic tanks, or any application where impact resistance, light weight and excellent dielectric properties are required. Fiberite 954-2A can be impregnated via hot melt or solution techniques on all available fibers and fabrics.

TYPICAL NEAT RESIN PROPERTIES

	RT	325°F (163°C)	325°F/Wet (163°C/Wet)	350°F (177°C)
Tensile Strength, ksi	10.0			
Tensile Modulus, Msi	0.44			
Tensile Ult. Strain, %	2.59			
Tensile Poisson's Ratio	0.38			
Tensile Strength, MPa	*68.9*			
Tensile Modulus, GPa	*3.03*			
Tensile Ult. Strain, %	*2.59*			
Tensile Poisson's Ratio	*0.38*			
Flexural Strength, ksi	16.9	13.5	11.9	12.6
Flexural Modulus, Msi	0.44	0.35	0.34	0.35
Flexural Strength, MPa	*117*	*93.1*	*82.0*	*86.9*
Flexural Modulus, GPa	*3.03*	*2.41*	*2.34*	*2.41*
H_2O Uptake, wt. %	1.28			
Tg (DMA-Tan δ), °C	215, 249			
Density, g/cm³	1.24			

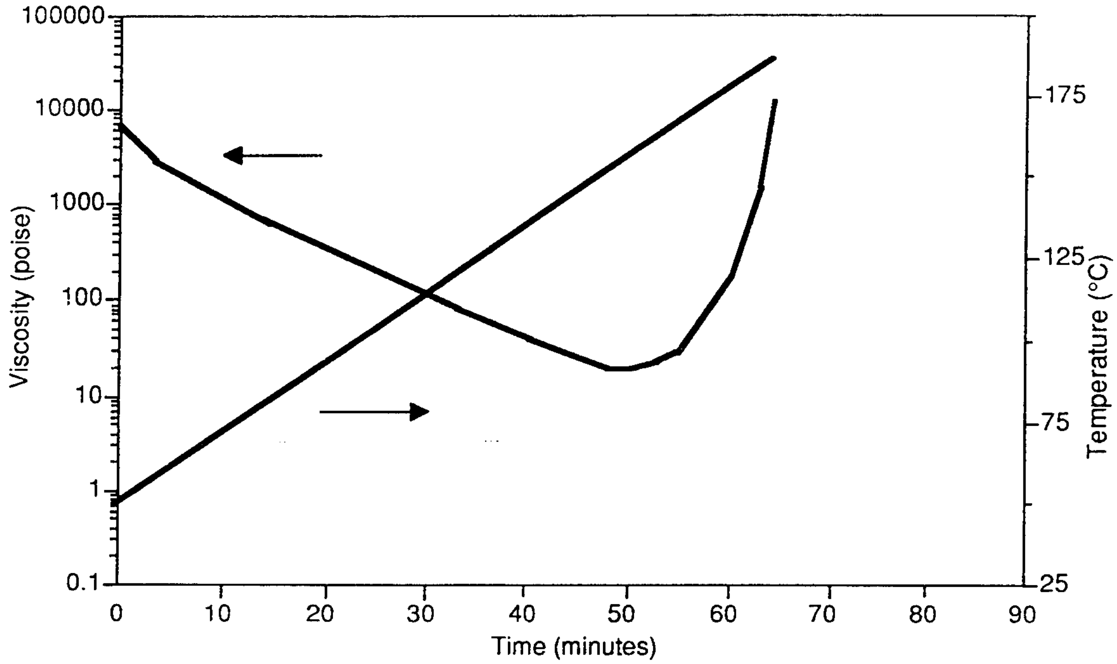
Notes: (1) Postcured 2 hours at 450°F
(2) Wet = Immersion at 160°F for 7 days

The data listed has been obtained from carefully controlled samples considered to be representative of the product described. Because the properties of this product can be significantly affected by the fabrication and testing techniques employed and since ICI Fiberite does not control the conditions under which its products are tested and used, ICI Fiberite cannot guarantee that the properties listed will be obtained with other processes and equipment.

TYPICAL PROPERTIES OF FIBERITE® 954-2A COMPOSITE LAMINATES

954-2A VISCOSITY PROFILE

Straight Heat-Up Cure Cycle to 350°F (177°C)



954-2A NEAT RESIN CURE STUDY

			350°F (177°C) Cure Only	With 450°F (232°C) Post Cure for 2 Hours
DSC Conversion (%)			84	>98
FTIR Converstion (%)			86	>97
T_g	G' (°C)		197	221
	Tan δ (°C)		220	212, 243
Flexure	300°F	Strength, ksi	16.20	16.4
		Modulus, Msi	0.40	0.42
	300°F/Wet	Strength, ksi	11.91	13.99
		Modulus, Msi	0.35	0.34
Moisture Uptake (%)			1.10	1.35
G_{IC}	(J/m^2)		333	242

Wet = Immersion at 160°F for 7 days.

A Data Sheet from

ICI FIBERITE

TYPICAL PROPERTIES OF FIBERITE® 954-2A COMPOSITE LAMINATES

INTERMEDIATE MODULUS (40 Msi) HERCULES IM-7 CARBON FIBER REINFORCED UNIDIRECTIONAL TAPE

Typical Fiberite Product Code: 1354-2AT

Cure: 4 hours @ 350°F; Post Cure: 2 hours @ 450°F

Mechanical Properties **DRY**	RT	300°F (149°C)	325°F (163°C)	350°F (177°C)
0° Tensile Strength, ksi (MPa)	388 (2675)			
0° Tensile Modulus, Msi (GPa)	23.2 (159.9)			
0° Compressive Strength, ksi (MPa)	206 (1420)		145 (999.7)	149 (1027)
Short Beam Shear Strength, ksi (MPa)	14.5 (100)	9.2 (63.4)	8.5 (58.6)	7.2 (49.6)
In-Plane Shear Modulus, Msi (GPa)	0.62 (4.27)			
90° Flexural Strength, ksi (MPa)	12.7 (87.6)			
Open Hole Compressive Strength[1], ksi (MPa)	41.4 (285.4)			
Compression After Impact Strength[2], ksi (MPa)	30.0 (206.8)			

Mechanical Properties **WET**	RT	300°F (149°C)	325°F (163°C)	350°F (177°C)
0° Compression Strength[3], ksi (MPa)		205(1413.4)		
Short Beam Shear Strength[3], ksi (MPa)		7.0 (48.3)	6.7 (46.2)	7.2 (49.6)
In-Plane Shear Modulus[4], Msi (GPa)		0.42 (2.89)	0.40 (2.76)	
Open Hole Compression Strength[1,5], ksi (MPa)		34.2(235.8)	32.5 (2241)	31.3 (1215.8)

Notes:
(1) $(+45, 0, -45, 90)_{2S}$ lay-up per BMS 8-276
(2) Specimens impacted and tested per BMS 8-276 at 1500 in-lbs/in.
(3) Wet = 1 week immersion in 160°F water
(4) Wet = Equilibrium at 85% RH at 150°F (66°C)
(5) Wet = 14 days immersion in 160°F (71°C) water

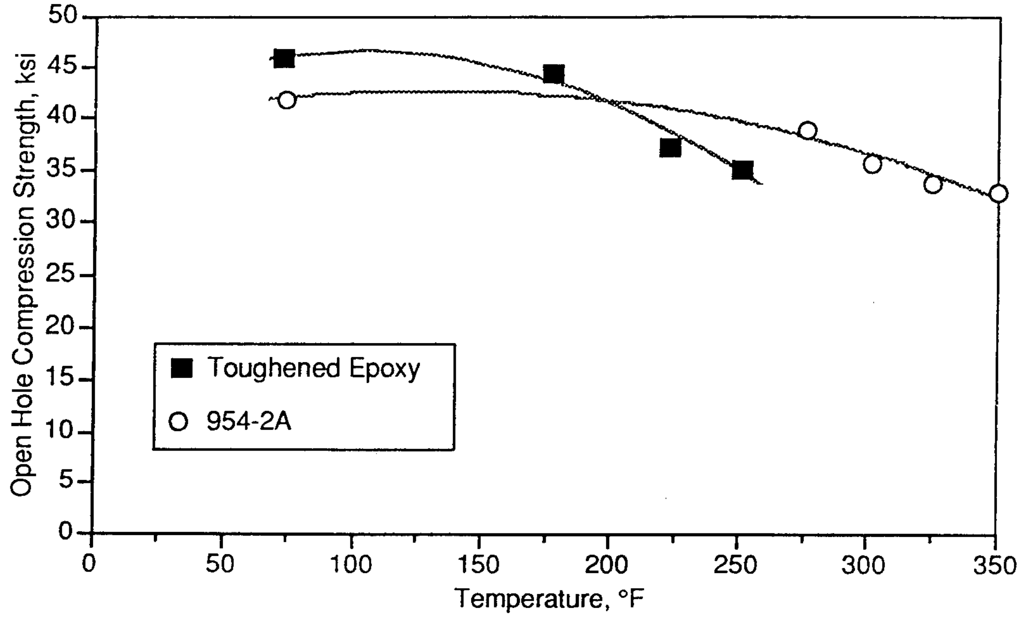
All of the above data was generated using 145 g/m² material.
Laminates used were between 56-60% fiber volume, and the resulting data was not normalized.

A Data Sheet from

FIBERITE

TYPICAL PROPERTIES OF FIBERITE® 954-2A COMPOSITE LAMINATES

OPEN HOLE COMPRESSION STRENGTH OF 954-2A/IM7 LAMINATES



954-2A PREPREG OUTLIFE STUDY

	DAY 1	DAY 14	DAY 28	DAY 42
Flow, %	15.48	14.87	13.44	12.70
DSC Peak (°C) Onset (°C)	 212 155	 213 168	 214 165	 205 156
Short Beam Shear, ksi RT 300°F	 14.5 9.2	 – –	 15.8 9.9	 16.1 9.5
Tack/Drape	y/y	y/y	n/y	n/y

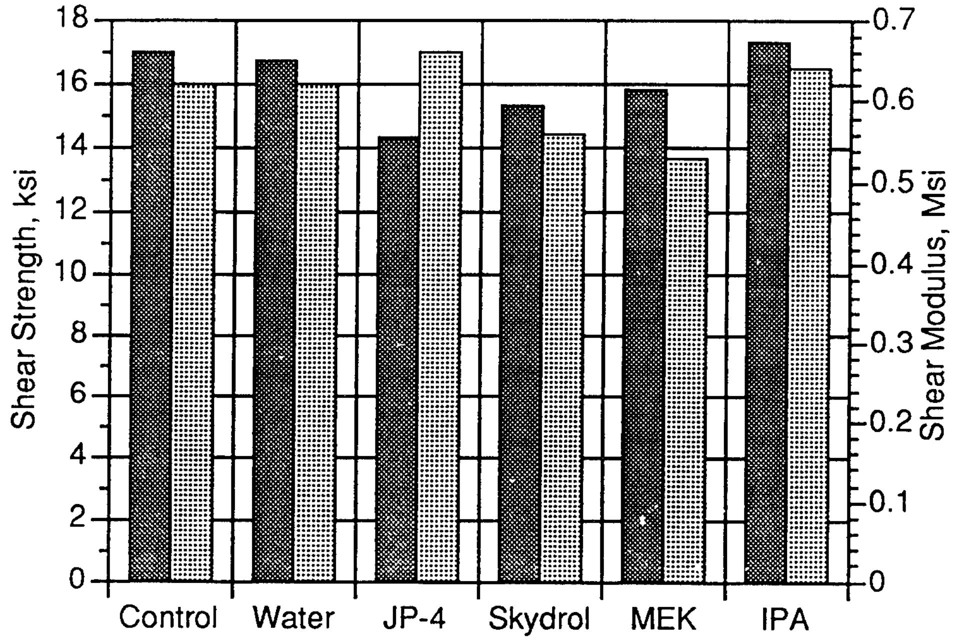
Samples cut and stored in sealed bag at RT until tested.
Prepreg 13(54-2A)T, Lot #26032, RC=35 ± 3%, FAW = 145 ± 5 g/m²

A Data Sheet from

FIBERITE

TYPICAL PROPERTIES OF FIBERITE® 954-2A COMPOSITE LAMINATES

SOLVENT SENSITIVITY OF Hy-E 1354-2AT



SOLVENT SENSITIVITY OF Hy-E 1354-2AT

	Control	Water	JP-4	Skydrol	MEK	IPA
±45 Tensile Strength, ksi ±45 Tensile Modulus, Msi	34.0 2.24	33.4 2.25	28.6 2.36	30.7 2.05	31.6 1.96	34.6 2.32
Shear Strength, ksi Shear Modulus, Msi	17.0 0.62	16.7 0.62	14.3 0.66	15.3 0.56	15.8 0.53	17.3 0.64
Poisson's Ratio	0.80	0.81	0.79	0.83	0.83	0.81
Shear Modulus Retention, %	–	100	106	90	85	103
Conditioning Temperature, °F	–	150	180	180	RT	RT
Weight Gain, %	–	0.43 Equil.	0.42 30 days	0.58 30 days	0.60 7 days	0.07 30 days

NOTES:
4-ply ±45 tensile samples tested at RT after indicated exposure
Material is Hy-E 13(54-2A)T, Lot 26040
Cure: 4 hours @ 350°F; 2 hours @ 450°F

A Data Sheet from

ICI FIBERITE

954-2A CYANATE RESIN

PRODUCT SAFETY

Material Safety Data Sheets for ICI Fiberite products can be obtained from the ICI Fiberite Safety, Health and Environmental Affairs Department in Winona, Minn. by calling (507) 454-3611.

PRODUCT HANDLING

The wearing of clean, impervious gloves is recommended when working with prepreg materials. Frozen prepreg should be brought to room temperature before opening bag. See Material Safety Data Sheet for more information.

SHIPPING

Prepreg is typically shipped as rolls in sealed aluminum or polyethylene bags in cardboard containers packed in dry ice.

DISPOSAL OF SCRAP

Disposal of material should be in accordance with local, state, and federal regulations, which may vary by location. Questions concerning disposal should be directed to the ICI Fiberite Safety, Health, and Environmental Affairs Department in Winona, Minn. for evaluation on a case-by-case basis.

A Data Sheet from

ICI FIBERITE

954-3 CYANATE RESIN

- Low microcracking, low moisture absorbing cyanate resin
- -200°F to 250°F (-128°C to 121°C) service temperature without post-cure. After post-cure, service temperature is 325°F/wet.
- Attractive electrical properties
- 350°F (177°C) cure
- Very low minimum viscosity
- Available in a broad range of fibers and forms including tape and fabric
- Autoclave or press-mold processable

Fiberite® 954-3 is a 350°F (177°C) curing cyanate resin with a -200°F to 250°F (-128°C to 121°C) service temperature. Fiberite 954-3 is formulated for autoclave or press molding. Standard cure is two hours at 350°F (177°C). Service temperatures are maximized by a post-cure of 428-450°F (220-232°C). Fiberite 954-3 can be impregnated via hot melt or solution techniques on all available fibers and fabrics. The recommended lay-up procedure for this material is L-7. The recommended cure procedure is C-9.

Typical applications for 954-3 include primary and secondary space structures and other applications where resistance to microcracking and moisture, together with light weight and excellent dielectric properties are required.

TYPICAL NEAT RESIN PROPERTIES

	RT	325°F (163°C)	325°F/Wet (163°C/Wet)
Tensile Strength, ksi	8.2		
Tensile Modulus, Msi	0.4		
Tensile Ult. Strain, %	2.4		
Tensile Strength, MPa	*56.5*		
Tensile Modulus, GPa	*2.76*		
Tensile Ult. Strain, %	*2.4*		
Flexural Strength, ksi	17.3	12.6	11.2
Flexural Modulus, Msi	0.43	0.33	0.30
Flexural Strength, MPa	*119.27*	*86.86*	*77.21*
Flexural Modulus, GPa	*2.96*	*2.28*	*2.07*
H_2O Uptake, Wt. %	0.96		
Tg (DMA-Tan δ), °C	258		
Density, g/cm³	1.19		

Notes: (1) Post-cured 2 hours at 450°F
(2) Wet = 7 day immersion at 160°F.

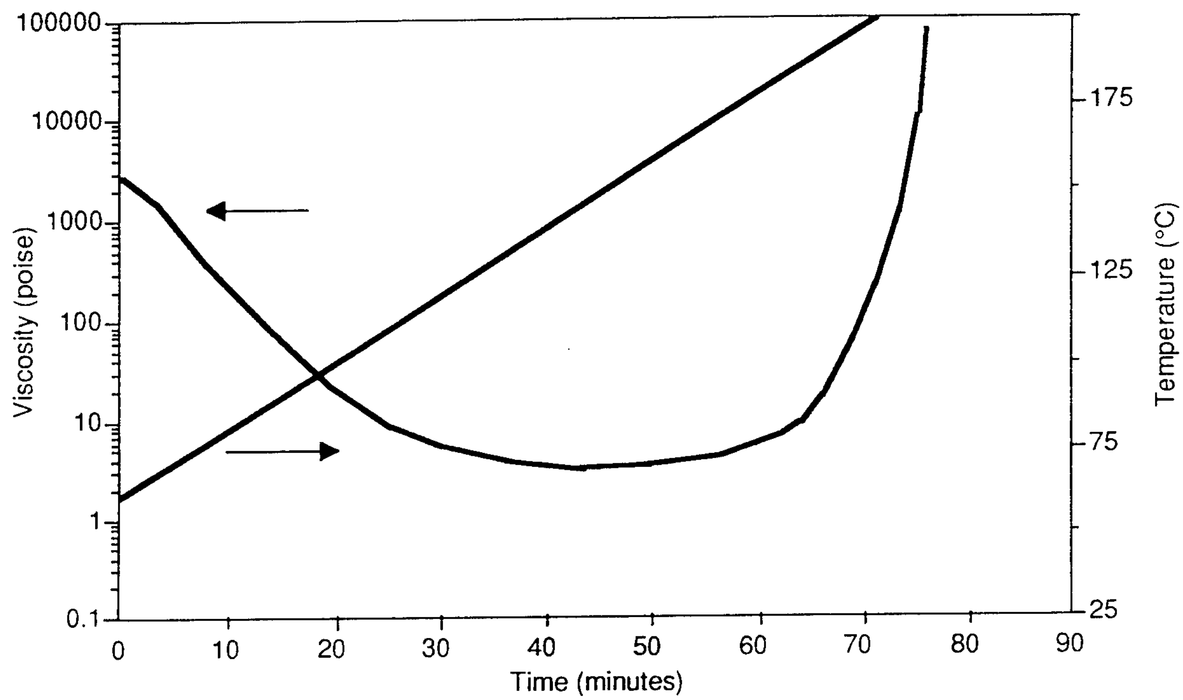
A Data Sheet from

FIBERITE

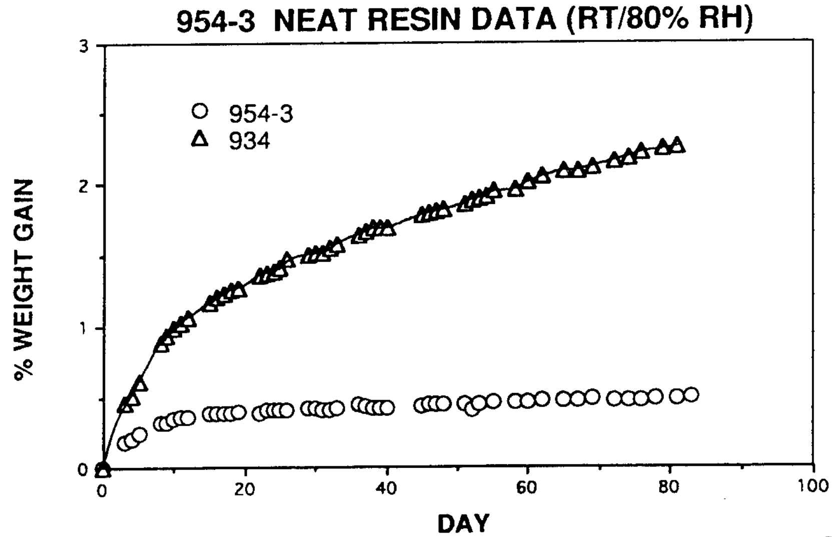
FIBERITE® 954-3 CYANATE RESIN

954-3 VISCOSITY PROFILE

Straight Heat-Up Cure Cycle to 350°F (177°C)



954-3 NEAT RESIN DATA (RT/80% RH)



The data listed has been obtained from carefully controlled samples considered to be representative of the product described. Because the properties of this product can be significantly affected by the fabrication and testing techniques employed and since ICI Fiberite does not control the conditions under which its products are tested and used, ICI Fiberite cannot guarantee that the properties listed will be obtained with other processes and equipment.

A Data Sheet from

ICI FIBERITE

TYPICAL PROPERTIES OF FIBERITE® 954-3 COMPOSITE LAMINATES

PROPERTIES SUMMARY FOR VARIOUS 70-90 MSI PITCH FIBERS IN FIBERITE 954-3 CYANATE RESIN

MATERIAL CODE, Hy-E		2054-3D	4054-3D	4954-3A	5054-3A
FIBER MANUFACTURER		AMOCO	TONEN	MITSUBISHI	NIPPON
FIBER DESIGNATION		P-75S 2K	FT-500MY 3K	K-135 2K U	XN-50A 2K
FIBER TENSILE MODULUS, Msi		75	70	90	75
FIBER TENSILE STRENGTH, ksi		275	430	500	530
FIBER ELONGATION, %		0.4	0.6	0.4	0.6
LAMINATE PROPERTIES					
0° Tensile	Strength, ksi	157	250	290	250
	Modulus, Msi	43	42	55	43
	Strain, %		0.58	0.53	
90° Tensile	Strength, ksi		4.3	3.9	5.3
	Modulus, Msi		0.93	0.82	0.73
	Strain, %		0.46	0.49	
0° Compressive	Strength, ksi	62	70	59	63
	Modulus, Msi	35	30	40	35
0° Flexural	Strength, ksi		110	99	100
	Modulus, Msi		30	42	33
90° Flexural	Strength, ksi		6	8.8	
	Modulus, Msi		0.90	0.80	
0° SB Shear	Strength, ksi	8.2	10	11	11

Notes:
1. These data are from various sources with varying numbers of tests. The data should be taken as a general indication of material's capabilities only.
2. All data are normalized to 60% fiber volume fraction except strain and SB Shear strength

MICROCRACK STUDIES FOR 954-3 vs. 934 ON PITCH 75 FIBER

	954-3	934
No. of Microcracks[1] $(0_2/90_2)_S$	49/inch	79/inch
No. of Microcracks[1] $(0/45/90/-45)_S$	30/inch	47/inch

Notes:

(1) Thermal cycling: 10 cycles, -184°F to +248°F, 10°F/min; ten minute dwell at -184°F and +248°F/10 min.

The data listed has been obtained from carefully controlled samples considered to be representative of the product described. Because the properties of this product can be significantly affected by the fabrication and testing techniques employed and since ICI Fiberite does not control the conditions under which its products are tested and used, ICI Fiberite cannot guarantee that the properties listed will be obtained with other processes and equipment.

A Data Sheet from

ICI FIBERITE

FIBERITE® 954-3 CYANATE RESIN

DIMENSIONAL STABILITY

	954-3[1]	934[2]
Hygrostrain, ppm	18.9	108.5
Water Absorption, %	0.18[3]	0.70[4]
CME, ppm/%	105	155

NOTES:
Hygrostrain divided by %M = CME
Pseudo-isotropic P75 laminates; 30% RC
[1]R. Brand and E. Derby; SPIE Conf, 1690, 309. April 1992 (Composite Optics, Inc.)
[2]C. Blair and J. Zakrzewski, SPIE Conf, 1690, 300. April 1992 (Lockheed MSC)
[3]55% RH/EQ
[4]50% RH/EQ

954-3 RESIN OUTGASSING

	954-3	ASTM LIMITS
Total Mass Loss	0.20%	1.0%
Volatile Condensable Materials	0.01%	0.1%
Water Vapor Recovered	0.04%	–

NOTES:
Tested per ASTM E 595

954-3 CYANATE RESIN

PRODUCT SAFETY

Material Safety Data Sheets for ICI Fiberite products can be obtained from the ICI Fiberite Safety, Health and Environmental Affairs Department in Winona, Minn. by calling (507) 454-3611.

PRODUCT HANDLING

The wearing of clean, impervious gloves is recommended when working with prepreg materials. See Material Safety Data Sheet for more information.

SHIPPING

Prepreg is typically shipped as rolls in sealed aluminum or polyethylene bags in cardboard containers packed in dry ice.

DISPOSAL OF SCRAP

Disposal of material should be in accordance with local, state, and federal regulations, which may vary by location. Questions concerning disposal should be directed to the ICI Fiberite Safety, Health, and Environmental Affairs Department in Winona, Minn. for evaluation on a case-by-case basis.

A Data Sheet from

FIBERITE

986 BISMALEIMIDE RESIN

- 355°F (180°C) cure with 450°F (232°C) unrestrained post cure

- Available in a broad range of fibers and forms including tape, fabric, and roving

- 425°F (218°C) dry and 325°F (107°C) wet service temperature with post cure

- Shelf life
  6 months at 0°F (-18°C)
  10 days at room temperature

Fiberite 986 resin is a 355°F (180°C) curing, bismaleimide resin with a service temperature of 400-425°F (205-218°C) dry and 300-325°F (150-163°C) wet. Unidirectional tapes and fabrics impregnated with 986 resin retain good tack for up to 30 days at room temperature. A post cure is required for high temperature usage.

Fiberite 986 can be impregnated via hot melt or solution techniques on all available fibers and fabrics.

Recommended lay-up procedure is L-7 or L-14. The recommended cure cycle for this material is C-5 or C-9 with unrestrained post cure at 450°F (232°C) for 4 to 6 hours.

Typical applications for Fiberite 986 include high temperature structural aircraft components.

TYPICAL NEAT RESIN PROPERTIES

	RT	350°F (177°C)	350°F WET (177°C WET)	450°F (232°C)
Flexural Strength, ksi	19	12	6	10
Flexural Modulus, Msi	0.66	0.44	0.25	0.38
Flexural Strength, MPa	*131*	*83*	*41*	*69*
Flexural Modulus, GPa	*4.6*	*3.0*	*1.7*	*2.6*
Tg, °C	285			
Density, g/cc	1.22			

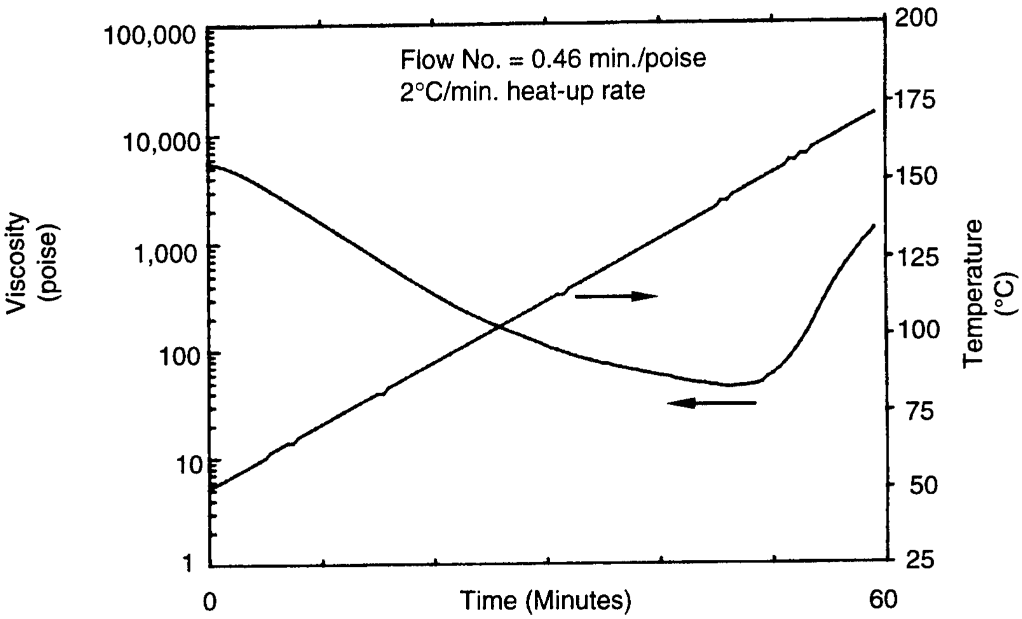
A Data Sheet from

ICI FIBERITE

986 BISMALEIMIDE RESIN

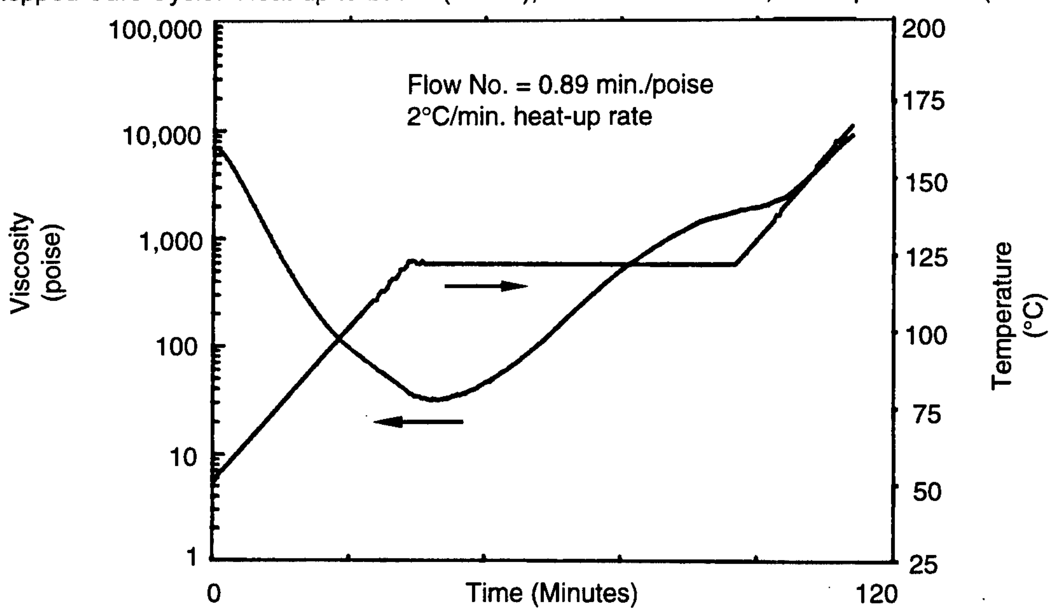
986 VISCOSITY PROFILE

Straight Heat-Up Cure Cycle to 350°F (177°C)



986 VISCOSITY PROFILE

Stepped Cure Cycle: Heat-up to 250°F (121°C), hold for 60 minutes, heat-up to 350°F (177°C)



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A Data Sheet from

ICI FIBERITE

TYPICAL PROPERTIES OF FIBERITE 986 COMPOSITE LAMINATES

HIGH STRENGTH (>500 ksi/3447 MPa)
STANDARD MODULUS (33 Msi/228 GPa CLASS)
CARBON FIBER REINFORCED
UNIDIRECTIONAL TAPE AND ROVING

Typical Fiberite Product Code
Hy-E 1686N

Mechanical Properties	**RT**	**375°F (190°C)**	**375°F WET (190°C WET)**	**420°F (215°C)**
0° Tensile Properties				
Strength, ksi	220-240			
Modulus, Msi	18-20			
Failure Strain, %	1.0-1.2			
Strength, MPa	*1517-1655*			
Modulus, GPa	*124-138*			
Failure Strain, %	*1.0-1.2*			
0° Compressive Properties				
Strength, ksi	230-260	160-180	150-170	140-160
Strength, MPa	*1586-1792*	*1103-1241*	*1034-1172*	*965-1103*
0° Flexural Properties				
Strength, ksi	330-350	200-220		
Modulus, Msi	18-21	18-21		
Strength, MPa	*2275-2413*	*1379-1517*		
Modulus, GPa	*124-145*	*124-145*		
Interlaminar Shear Properties				
Strength, ksi	18-20	10-12	7-9	8-10
Strength, MPa	*124-138*	*69-83*	*48-62*	*55-69*

Property values listed are typical for laminates with 57 to 63% fiber volume.
Wet = 7 day water immersion @ 165°F (74°C).

A Data Sheet from

ICI FIBERITE

TYPICAL PROPERTIES OF FIBERITE 986 COMPOSITE LAMINATES

HIGH STRENGTH (>500 ksi/3447 MPa) STANDARD MODULUS (33 Msi/228 GPa CLASS) CARBON FIBER REINFORCED 5 HARNESS SATIN FABRIC

Typical Fiberite Product Code
HMF 2323/86

Mechanical Properties	RT	400°F (205°C)	400°F WET (205°C WET)
0° Tensile Properties			
Strength, ksi	120-135	120-135	110-130
Modulus, Msi	8-11	8-11	8-11
Strain (%)	1.1-1.3	1.1-1.3	1.1-1.3
Strength, MPa	*827-931*	*827-931*	*758-896*
Modulus, GPa	*55-76*	*55-76*	*55-76*
Strain (%)	*1.1-1.3*	*1.1-1.3*	*1.1-1.3*
0° Compressive Properties			
Strength, ksi	70-120	70-90	40-60
Modulus, Msi	8-10	8-10	8-10
Strength, MPa	*483-827*	*483-620*	*276-414*
Modulus, GPa	*55-69*	*55-69*	*55-69*
0° Flexural Properties			
Strength, ksi	160-180	120-140	90-110
Modulus, Msi	8-11	8-11	8-11
Strength, MPa	*1103-1241*	*827-965*	*620-758*
Modulus, GPa	*55-76*	*55-76*	*55-76*
Interlaminar Shear Properties			
Strength, ksi	8-10	6-8	4-6
Strength, MPa	*124-138*	*110-124*	*55-69*

Property values listed are typical for laminates with 55 to 60% fiber volume.
Wet = 7 day water immersion @ 165°F (74°C).

A Data Sheet from

ICI FIBERITE

TYPICAL PROPERTIES OF FIBERITE 986 COMPOSITE LAMINATES

E-GLASS FIBER REINFORCED
8 HARNESS SATIN FABRIC

Typical Fiberite Product Code
MXB 986/7781

Mechanical Properties	**RT**	**450°F (232°C)**
0° Tensile Properties		
Strength, ksi	70-80	60-70
Strength MPa	*483-552*	*414-483*
0° Flexural Properties		
Strength, ksi	110-130	100-110
Strength, MPa	*758-896*	*689-758*

Property values listed are typical for laminates with 50 to 55% fiber volume.

The data listed has been obtained from carefully controlled samples considered to be representative of the product described. Because the properties of this product can be significantly affected by the fabrication and testing techniques employed and since ICI Fiberite does not control the conditions under which its products are tested and used, ICI Fiberite cannot guarantee that the properties listed will be obtained with other processes and equipment.

986 BISMALEIMIDE RESIN

PRODUCT SAFETY

Material Safety Data Sheets for ICI Fiberite products can be obtained from the ICI Fiberite Safety, Health and Environmental Affairs Department in Winona, Minn. by calling (507) 454-3611.

PRODUCT HANDLING

The wearing of clean, impervious gloves is recommended when working with prepreg materials. See Material Safety Data Sheet for more information.

SHIPPING

Prepreg is typically shipped as rolls in sealed aluminum or polyethylene bags in cardboard containers packed with dry ice.

DISPOSAL OF SCRAP MATERIAL

Disposal of material should be in accordance with local, state, and federal regulations, which may vary by location. Questions concerning disposal should be directed to the ICI Fiberite Safety, Health, and Environmental Affairs Department in Winona, Minn. for evaluation on a case-by-case basis.

A Data Sheet from

ICI FIBERITE

966D POLYIMIDE RESIN

- NASA-formulated PMR-15 modified for low NE-MDA content
- Available in a broad range of fibers and forms including unidirectional tape and fabric
- Projected use in gas turbine engines, aerospace, and for 600°F (315°C) service temperature applications
- 600°F (315°C)/ 200 psi (1.38 MPa) autoclave cure with 600°F (315°C) freestanding post cure
- Good thermo-oxidative stability
- Autoclave or press-mold processing
- Shelf life
  6 months at 0°F (-18°C)
  10 days at room temperature (minimum)

Fiberite® 966D is a NASA-formulated, ICI Fiberite manufactured high temperature polyimide resin. It has the same formulation as 966C but with a significantly lower NE-MDA content, which increases prepreg outtime. It can be autoclave cured at 600°F (315°C), 200 psi (1.38 MPa) pressure, with either bleed or no-bleed lay-up. A 600°F (315°C) freestanding post cure will give the composite a service temperature of 550-600°F(288-315°C). 966D can also be press molded.

Typical applications include aircraft engines and aerospace structures where high service temperatures are required.

Fiberite® 966D can be impregnated on all available fibers and fabrics. However, unidirectional tapes are limited to 24-inch widths. The recommended lay-up procedure for 966D is L-12. Recommended cure cycles are C-14 with C-15 (a two-step procedure) or C-24 which is a single-step procedure.

TYPICAL NEAT RESIN PROPERTIES

	RT
Tensile Strength, ksi	8
Tensile Modulus, Msi	0.47
Tensile Strength, MPa	*55*
Tensile Modulus, GPa	*3.2*
Compressive Yield Strength, ksi	16
Compressive Strength, ksi	27
Compressive Yield Strength, MPa	*110*
Compressive Strength, MPa	*186*
Tg, °C (nominal)	315
Density, g/cc	1.32

The data listed has been obtained from carefully controlled samples considered to be representative of the product described. Because the properties of this product can be significantly affected by the fabrication and testing techniques employed and since ICI Fiberite does not control the conditions under which its products are tested and used, ICI Fiberite cannot guarantee that the properties listed will be obtained with other processes and equipment.

A Data Sheet from

ICI FIBERITE

TYPICAL PROPERTIES OF FIBERITE® 966D COMPOSITE LAMINATES

HIGH STRENGTH (>500 ksi/3447 MPa)
STANDARD MODULUS (33 Msi/228 GPa CLASS)
CARBON FIBER REINFORCED
8 HARNESS SATIN FABRIC

Typical Fiberite Product Code
HMF 2474/66D

Mechanical Properties	**RT**	**550°F (288°C)**
0° Tensile Properties		
Strength, ksi	100-130	110-140
Modulus, Msi	9-11	9-11
Strength, MPa	*689-896*	*758-965*
Modulus, GPa	*62-76*	*62-76*
0° Compressive Properties		
Strength, ksi	80-100	60-80
Modulus, Msi	9-11	7-9
Strength, MPa	*552-689*	*414-552*
Modulus, GPa	*62-76*	*48-62*
0° Flexural Properties		
Strength, ksi	140-160	100-130
Modulus, Msi	8-10	8-10
Strength, MPa	*965-1103*	*689-896*
Modulus, GPa	*55-69*	*55-69*
Interlaminar Shear Properties		
Strength, ksi	8-10	5-7
Strength, MPa	*55-69*	*34-48*

Property values listed are typical for laminates with 55 to 60% fiber volume.

966D POLYIMIDE RESIN

PRODUCT SAFETY

Material Safety Data Sheets for ICI Fiberite products can be obtained from the ICI Fiberite Safety, Health and Environmental Affairs Department in Winona, Minn. by calling (507) 454-3611.

PRODUCT HANDLING

The wearing of clean, impervious gloves is recommended when working with prepreg materials. See Material Safety Data Sheet for more information.

SHIPPING

Prepreg is typically shipped as rolls in sealed aluminum or polyethylene bags in cardboard containers packed with dry ice.

DISPOSAL OF SCRAP MATERIAL

Disposal of material should be in accordance with local, state, and federal regulations, which may vary by location. Questions concerning disposal should be directed to the ICI Fiberite Safety, Health, and Environmental Affairs Department in Winona, Minn. for evaluation on a case-by-case basis.

APPENDIX E

PARTS FABRICATOR PERSPECTIVES

Workshop

Closed-Mold Manufacturing of High Performance Composite Missile Structures

15-16 May 1995

Parts Fabricators Session

Jerry Lehman
(314)233-5824

McDonnell Douglas Aerospace

Related MDA Experience

Low Cost Composite Weapons (LCCW)

- Eglin AFB, AFATL/FXV
- F08635-88-C-0131

Resin Transfer Molding

- GreatLakes Composites Consortium (GLCC)
- TDL 91-07

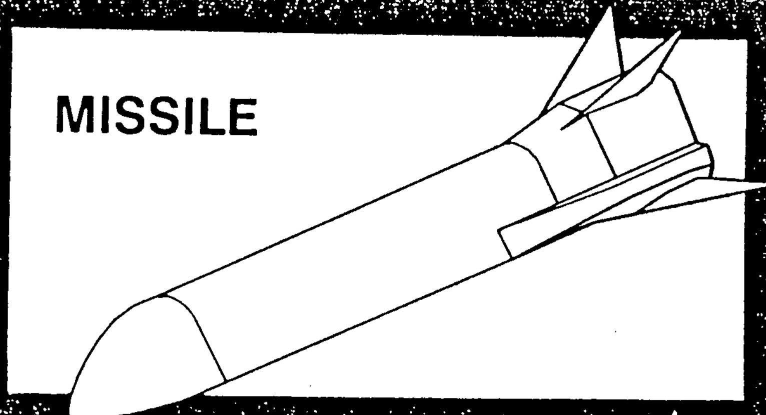
RTM Implementation of F/A-18E/F

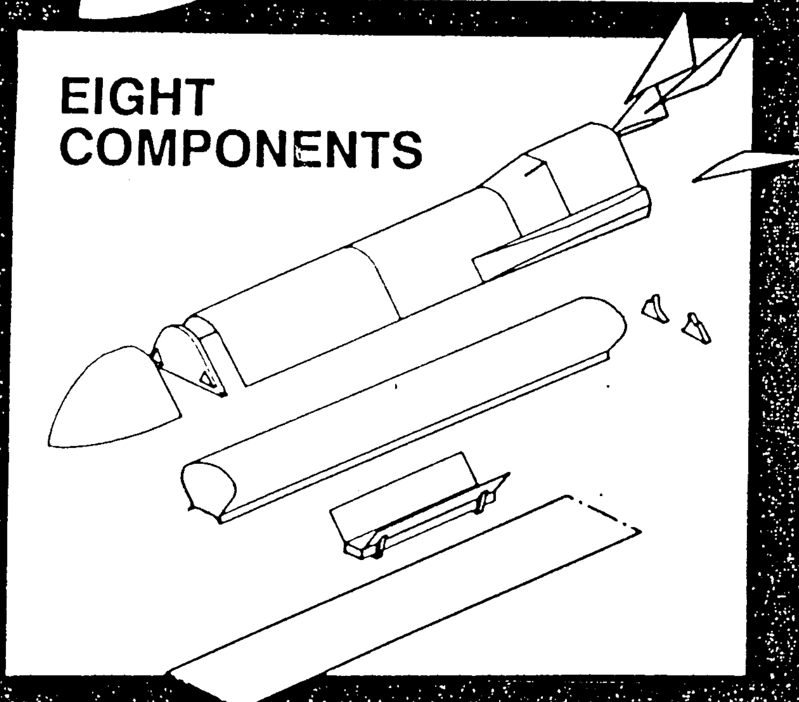
- Outer Wing Leading Edge Seals
- Material and Process Specifications
- Design Allowables

IRAD

LOW COST COMPOSITE WEAPONS (LCCW)

27 FEB 90





PURPOSE

Develop broad technology base in low cost weapon construction

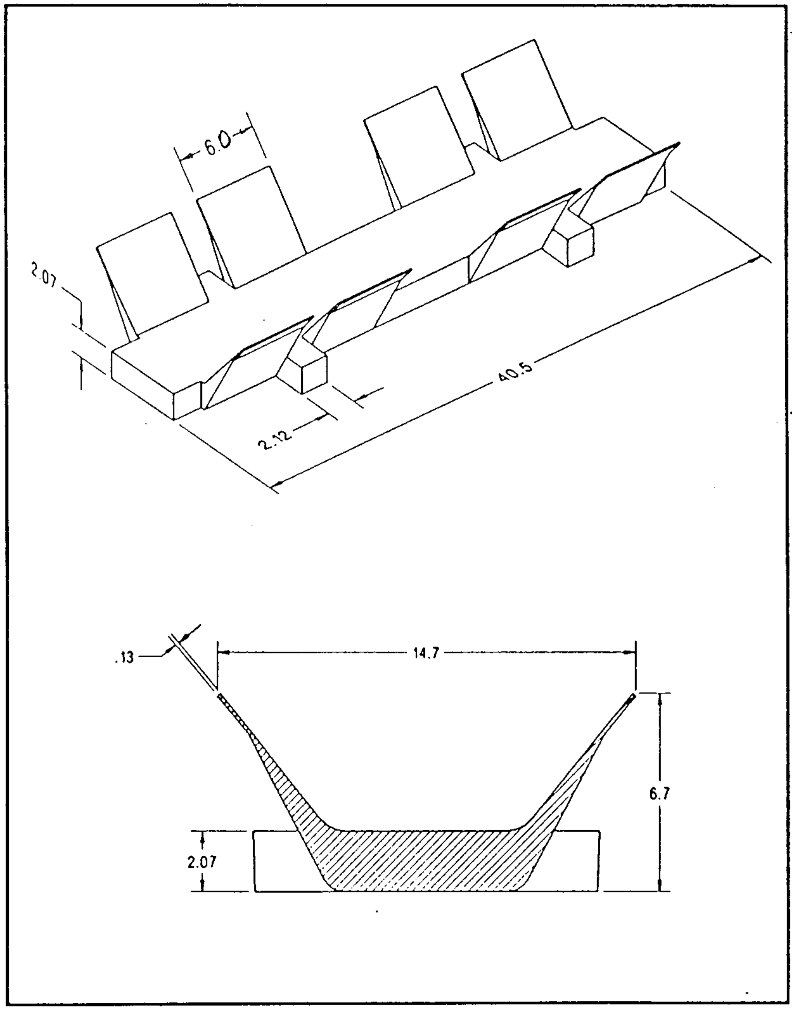
ACTIVITY

Technical evaluation, tooling, fabrication, assembly, testing, production costs, design guidelines

TECHNOLOGIES

- Processes
  - Resin transfer molding
  - Pultrusion
  - Compression molding
  - Diaphragm forming
  - Stamping
  - Roll forming
  - Ply Stacking
  - Injection molding
- Materials
  - Thermoplastics
  - Thermosets
- Assembly approaches
- In-process control

RTM STRONGBACK



MATERIALS:

CARBON/EPOXY (PREFORM)

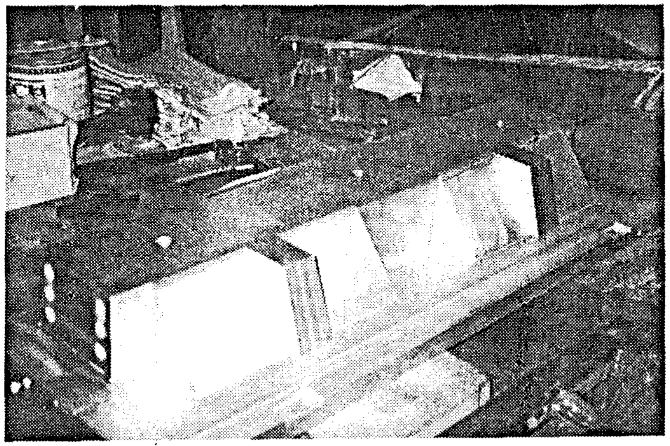
FABRICATOR:

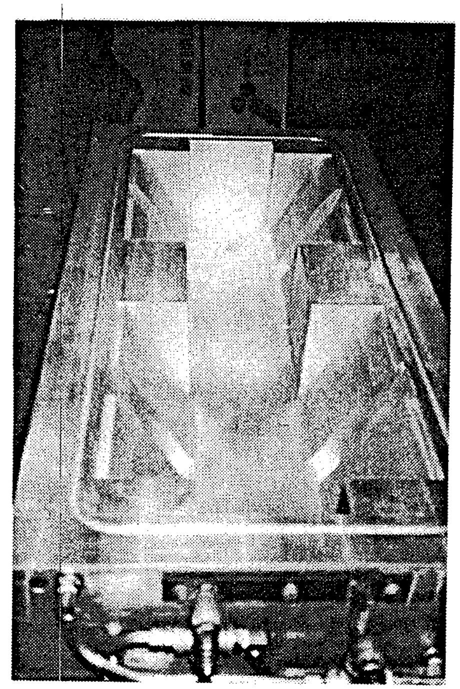
DESIGN EVOLUTIONS 4, INC.

SUPPLIERS:

HEXCEL/HITECH
SHELL CHEMICAL CO.

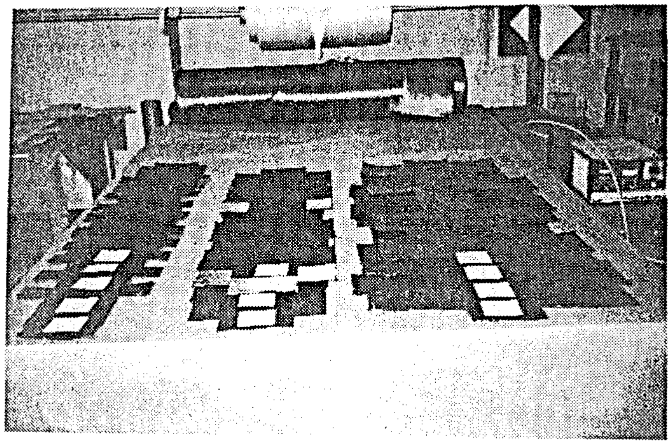
RTM STRONGBACK TOOLING



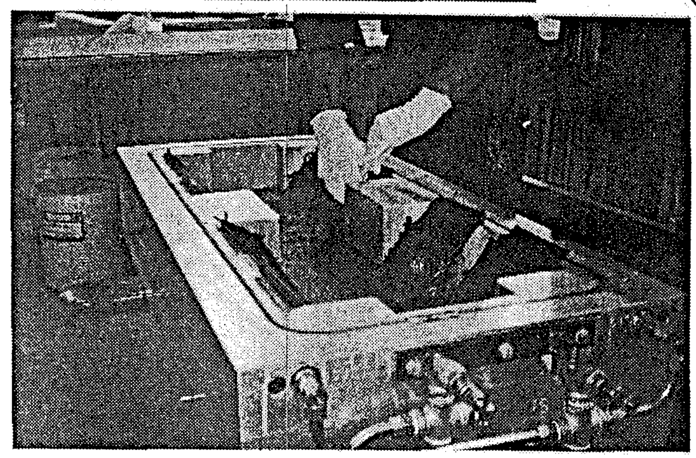


The integrally heated aluminum Strongback tool includes 3 injection ports and multiple bleed vents for air removal.

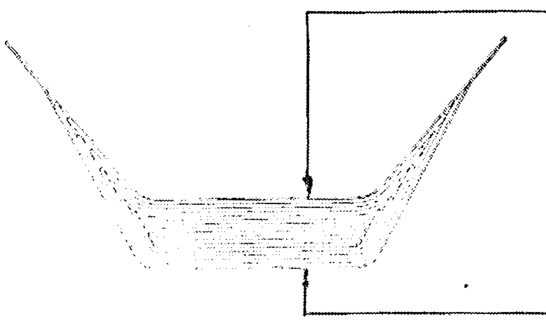
RTM STRONGBACK FABRICATION



1 - FABRICATE PREFORM



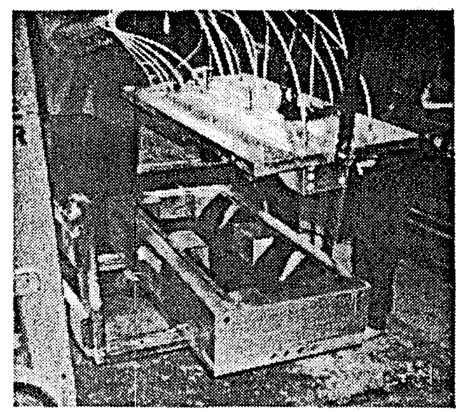
2 - PLACE PREFORM IN MOLD



PLY SCHEDULE	
PLY NO.	LAYUP
1	A
2	B
3	C
4	B
5	C
6	B
7	C
8	B
9	B
10	C
11	B
12	B
13	C
14	B
15	C
16	B
17	C
18	B
19	A

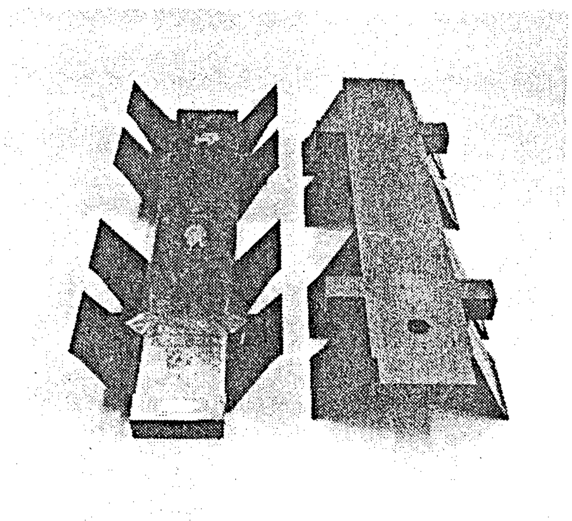
A: (0, 90, +45, -45)
B: (0, 90, 90, 0)
C: (-45, +45, +45, -45)

PREFORM DESIGN



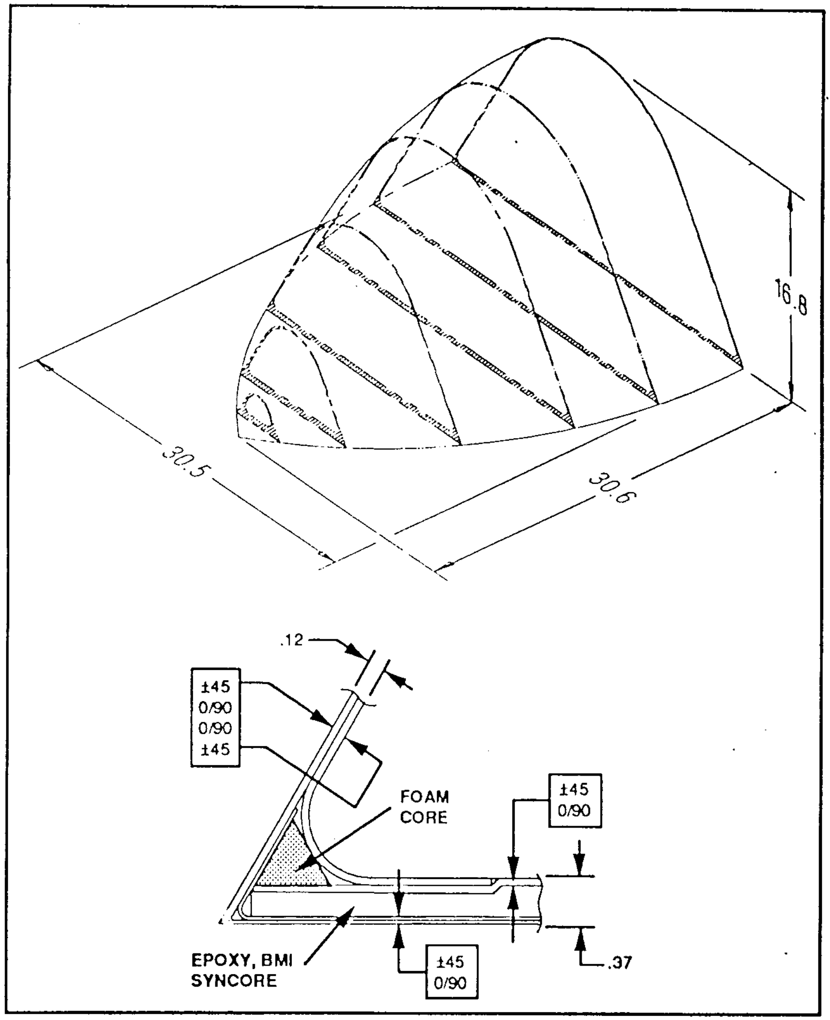
3 - CLOSE MOLD, INJECT RESIN AND CURE

RTM STRONGBACK "LESSONS LEARNED"



- IMPROVE PREFORM TOLERANCE CONTROL
- USE DUPLICATE PART TOOLING TO FABRICATE PREFORM
- INCORPORATE TOOL EJECTOR SYSTEM TO EASE PART REMOVAL
- MINIMIZE NUMBER OF VENTS TO DECREASE TOOL PREPARATION TIME

RTM NOSE



MATERIALS:

E-GLASS/SYNCORE/EPOXY
E-GLASS/SYNCORE/BMI

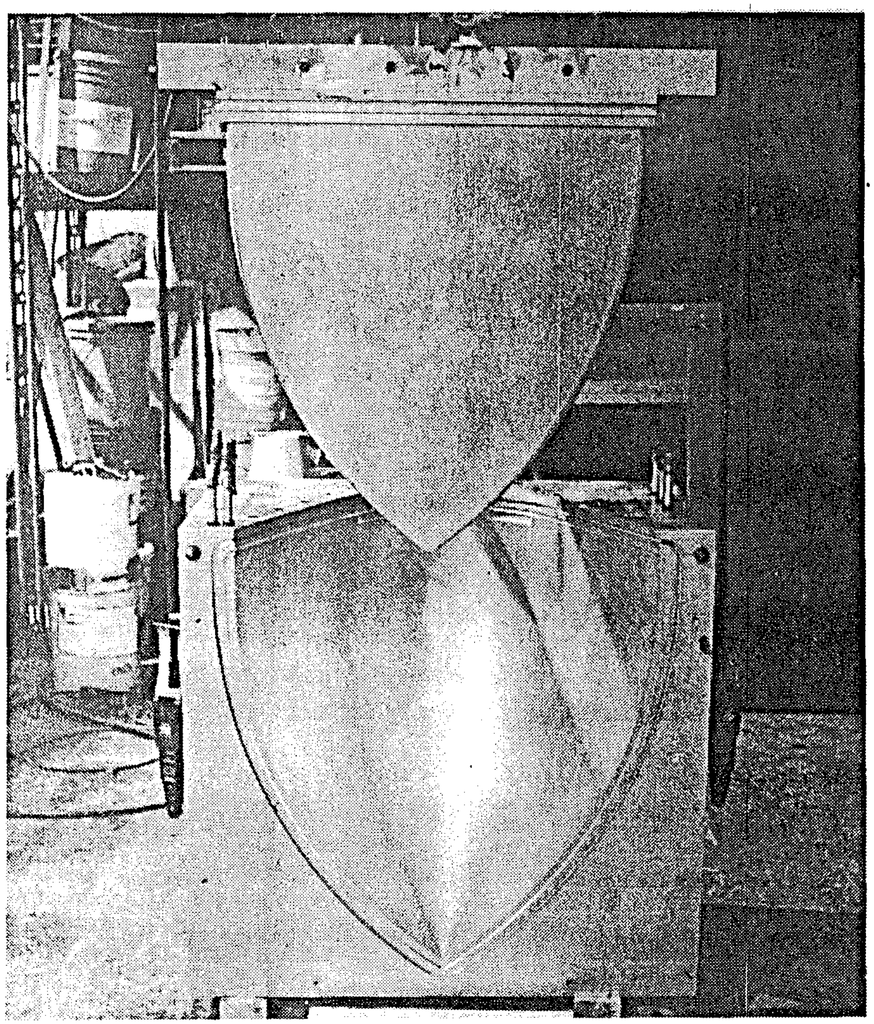
FABRICATOR:

DESIGN EVOLUTIONS 4, INC.

SUPPLIERS:

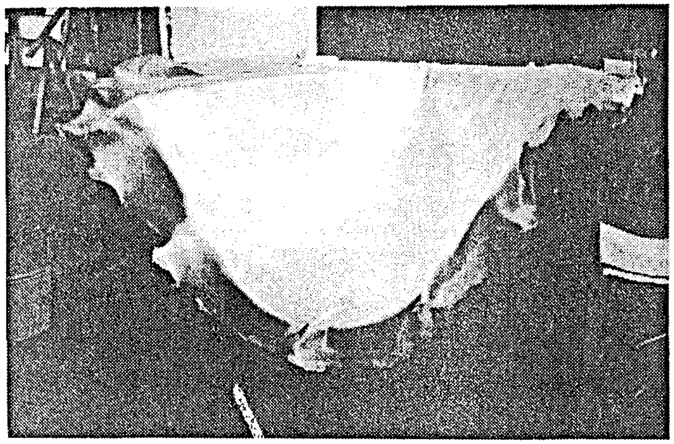
HEXCEL/HITECH
SHELL CHEMICAL CO.
DEXTER HYSOL

RTM NOSE TOOLING

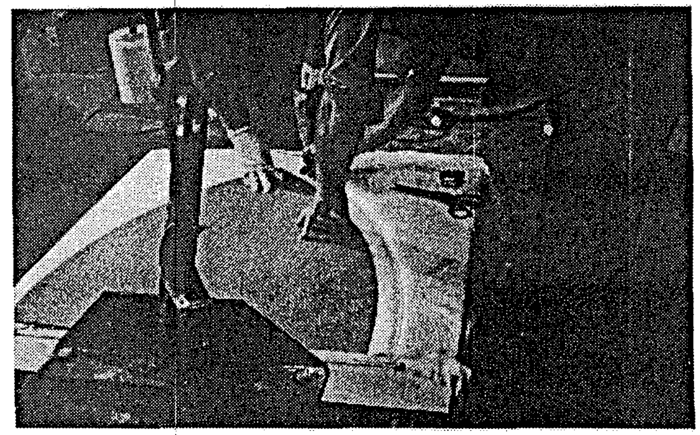


The integrally heated, 3 piece aluminum Nose tool has a segmented core , 2 injection ports, and 4 bleed vents for air removal.

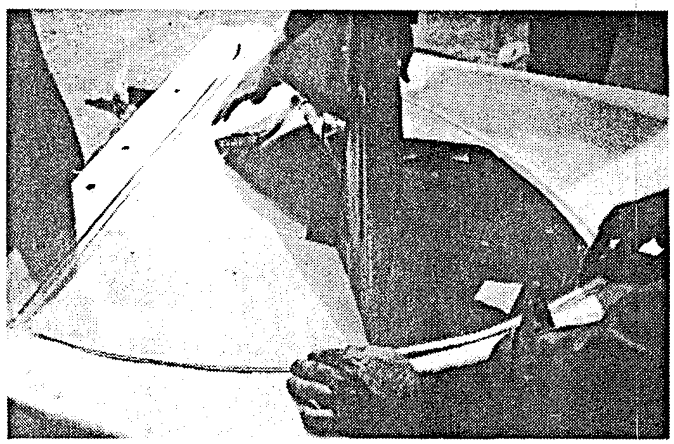
RTM NOSE FABRICATION



1 - LAY UP UPPER CONTOUR MATERIAL

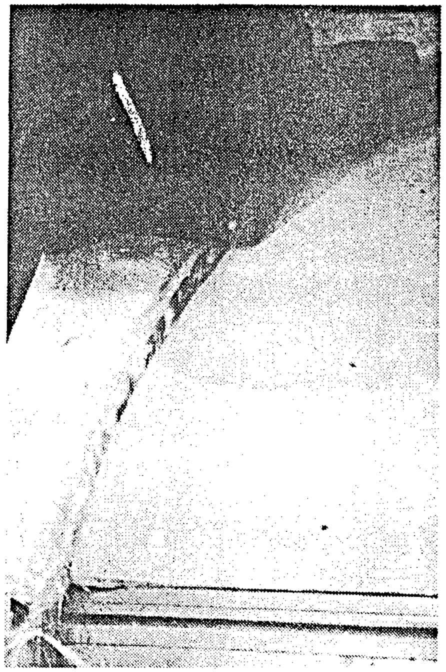


2 - TRIM OVERLAP AREA

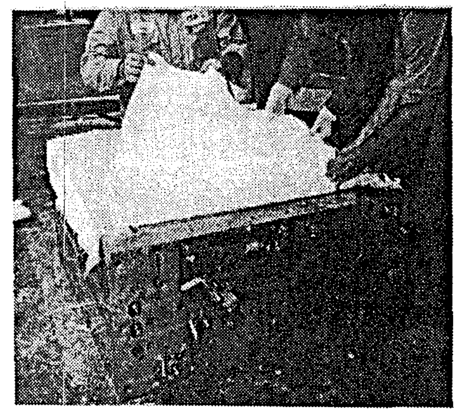


3 - PLACE SYNCORE IN LOWER PANEL

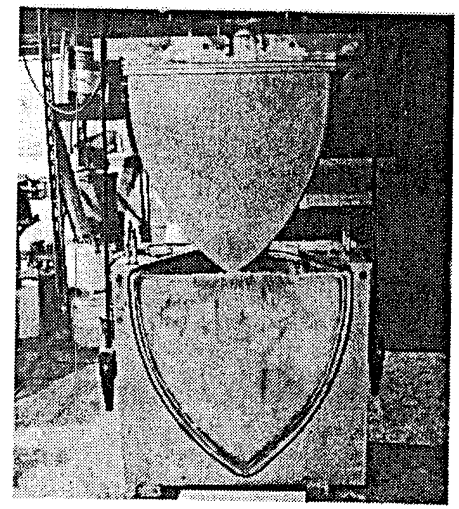
RTM NOSE FABRICATION



4 - ADD ROVINGS TO CORNER FILLET AREA

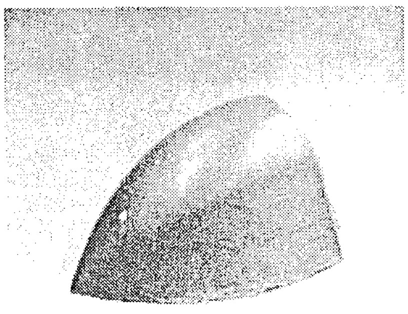


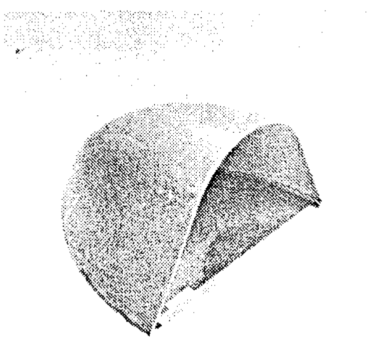
5 - LAY UP LOWER PANEL PLIES



6 - INJECT, CURE AND DEMOLD

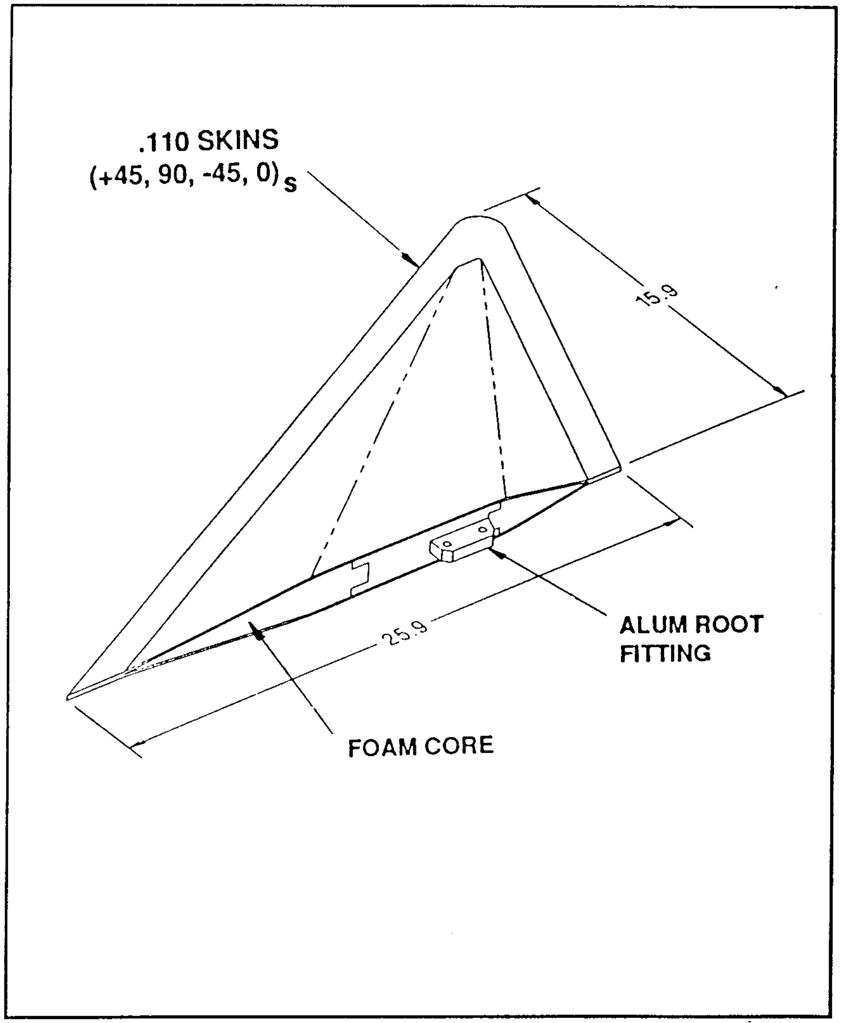
RTM NOSE "LESSONS LEARNED"





- DO NOT USE SYNCORE WITH RTM PROCESS
- STITCHED MATERIAL CAN BE USED ON CONTOURED PARTS WITHOUT WRINKLING
- INJECTION SEQUENCE AND PLY CONFIGURATION IMPACTS FIBER MOVEMENT IN THE MOLD

RTM FIN



MATERIALS:

CARBON/EPOXY (STITCHED)
CARBON/BMI (STITCHED)
FOAM CORE
ALUMINUM FITTING

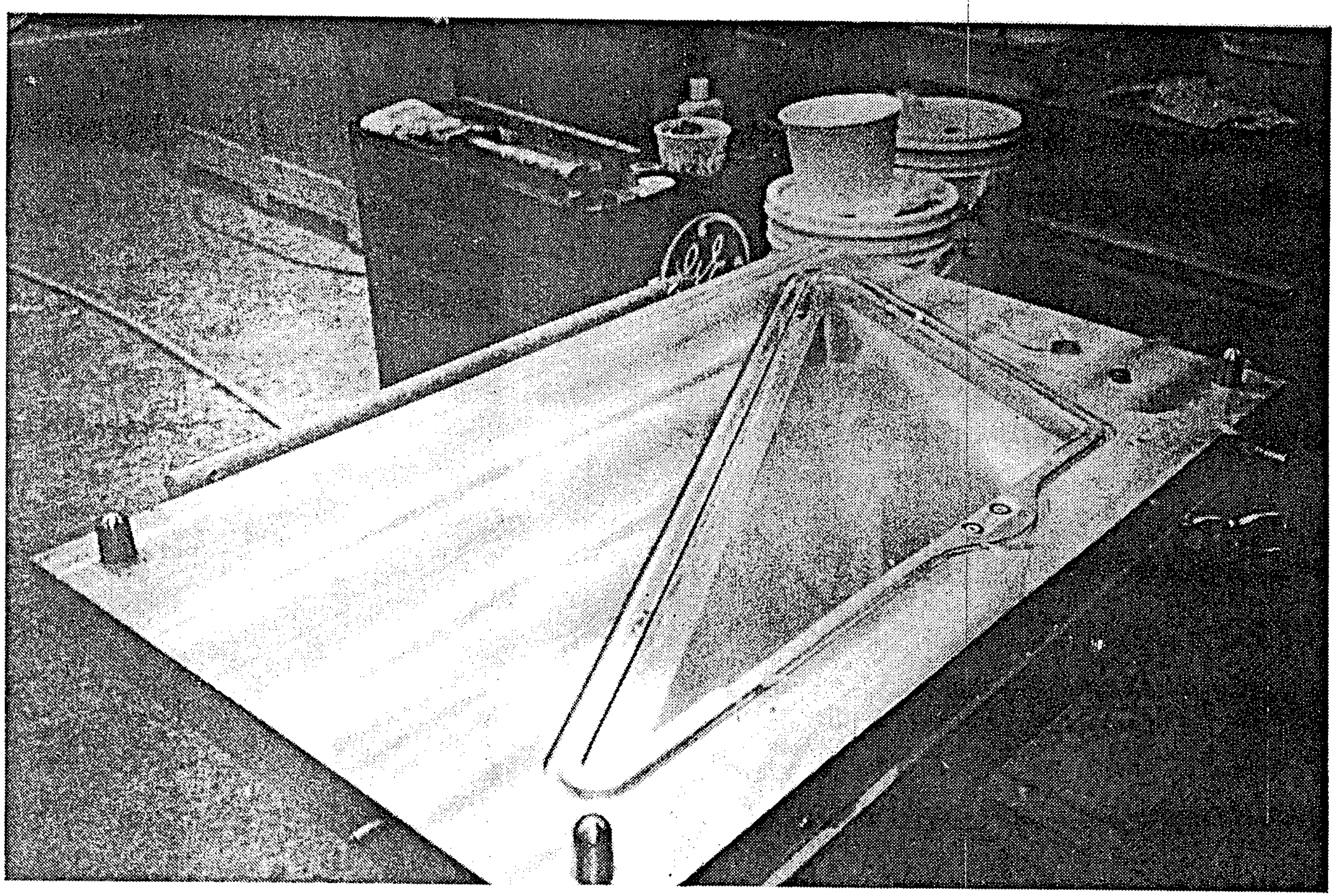
FABRICATOR:

DESIGN EVOLUTIONS 4, INC.

SUPPLIERS:

HEXCEL/HITECH
SHELL CHEMICAL CO.
ROHM TECH

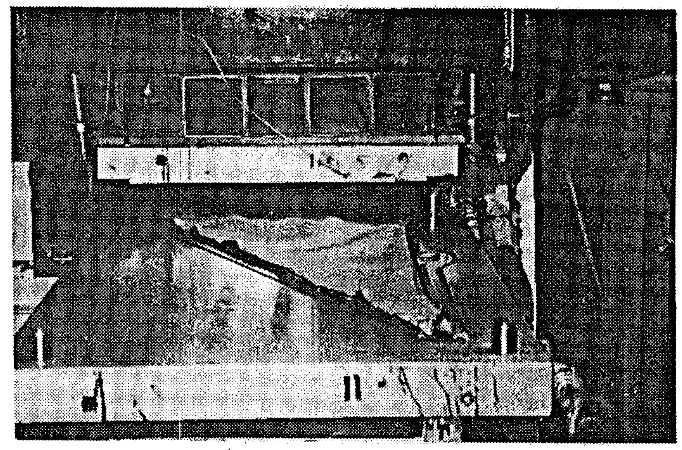
RTM FIN TOOLING



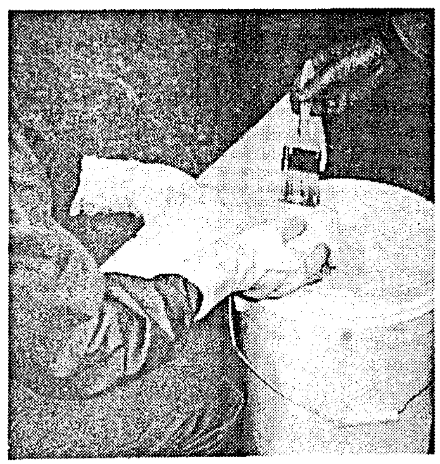
The integrally heated, aluminum Fin tool has a manifold gate at the base and 1 vent at the tip for air removal.

RTM FIN FABRICATION

1 - CUT STITCHED MATERIAL PLIES

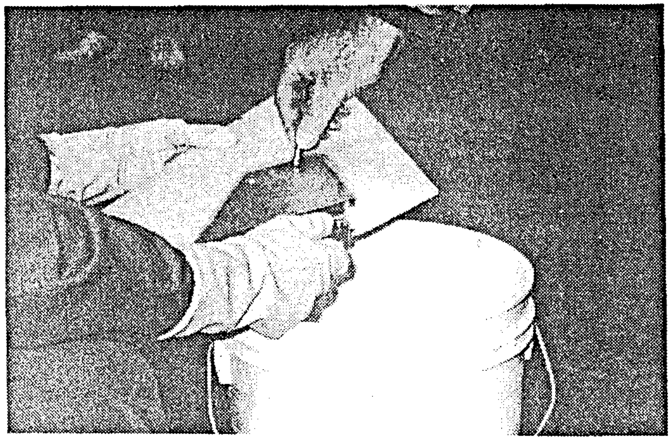


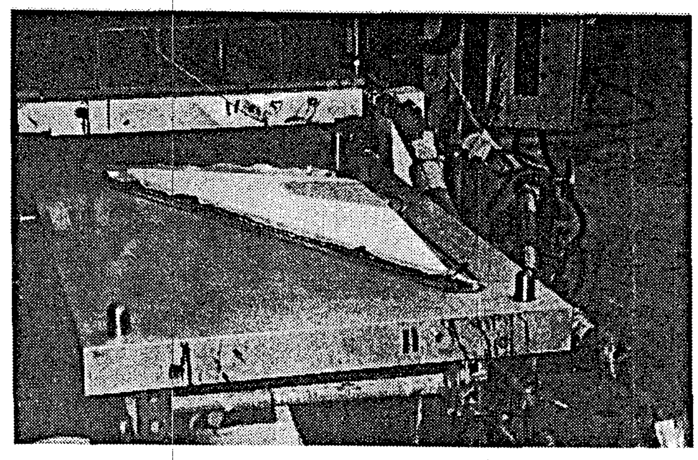
2 - LAY UP PLIES INTO MOLD CAVITY

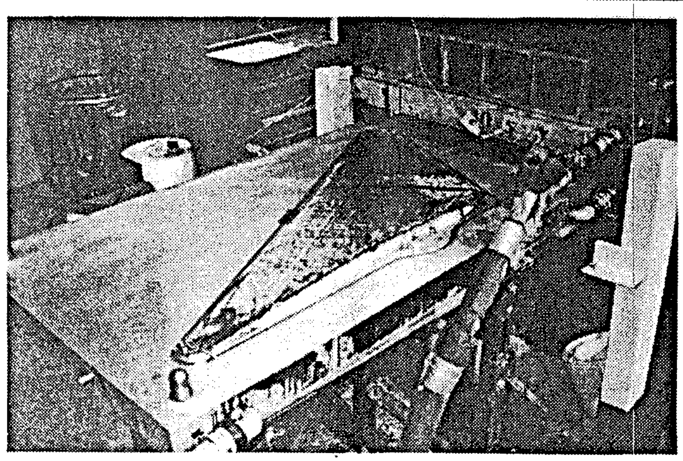


3 - APPLY RESIN TO FOAM IN FITTING AREA

RTM FIN FABRICATION

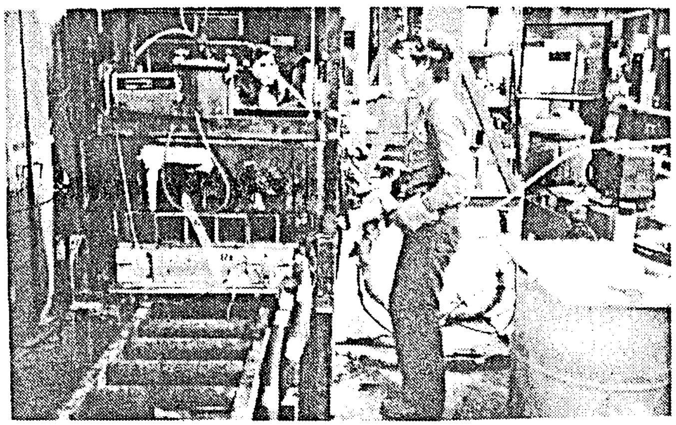

4 - INSTALL ALIGNMENT PINS AND FITTING


5 - PLACE CORE/FITTING ASSY INTO MOLD


6 - LAY UP PLIES ONTO CORE/FITTING ASSY

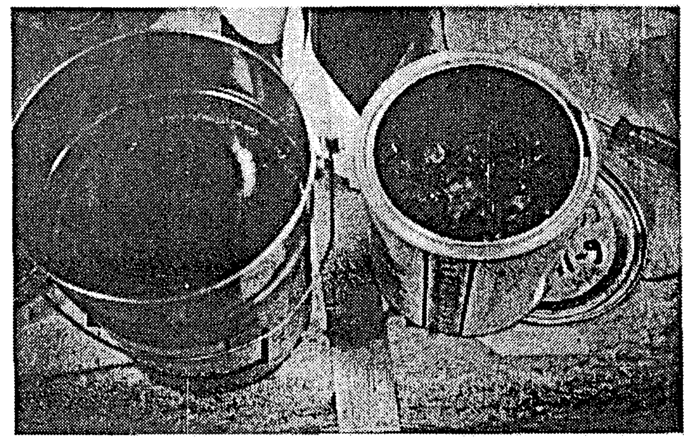
RTM FIN FABRICATION

EPOXY RESIN INJECTION

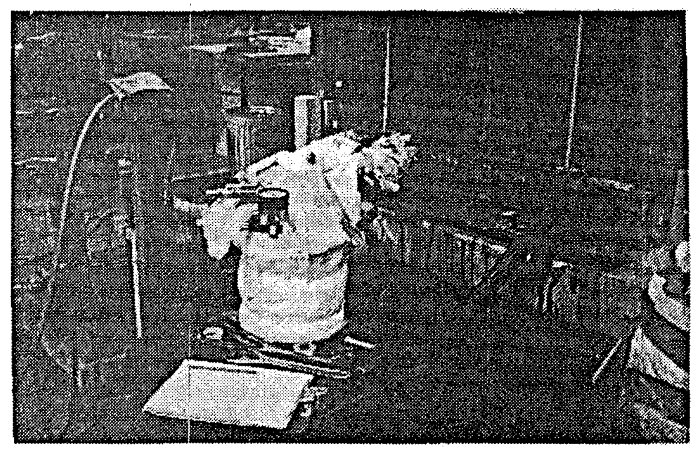


7 - MIX RESIN AND INJECT USING LIQUID CONTROL EQUIPMENT

BMI RESIN INJECTION

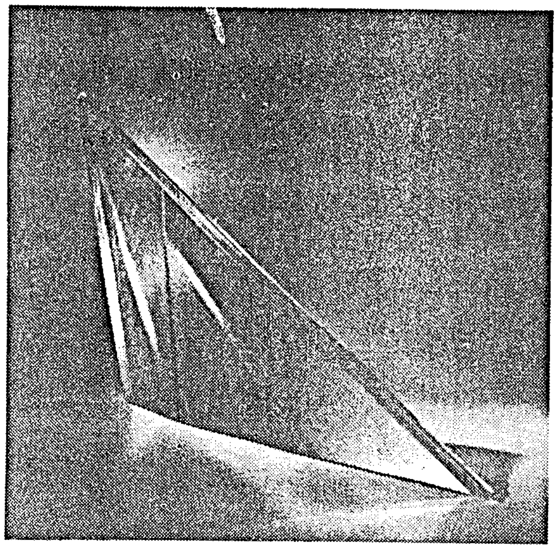


7A - BREAK UP RESIN AND PREHEAT



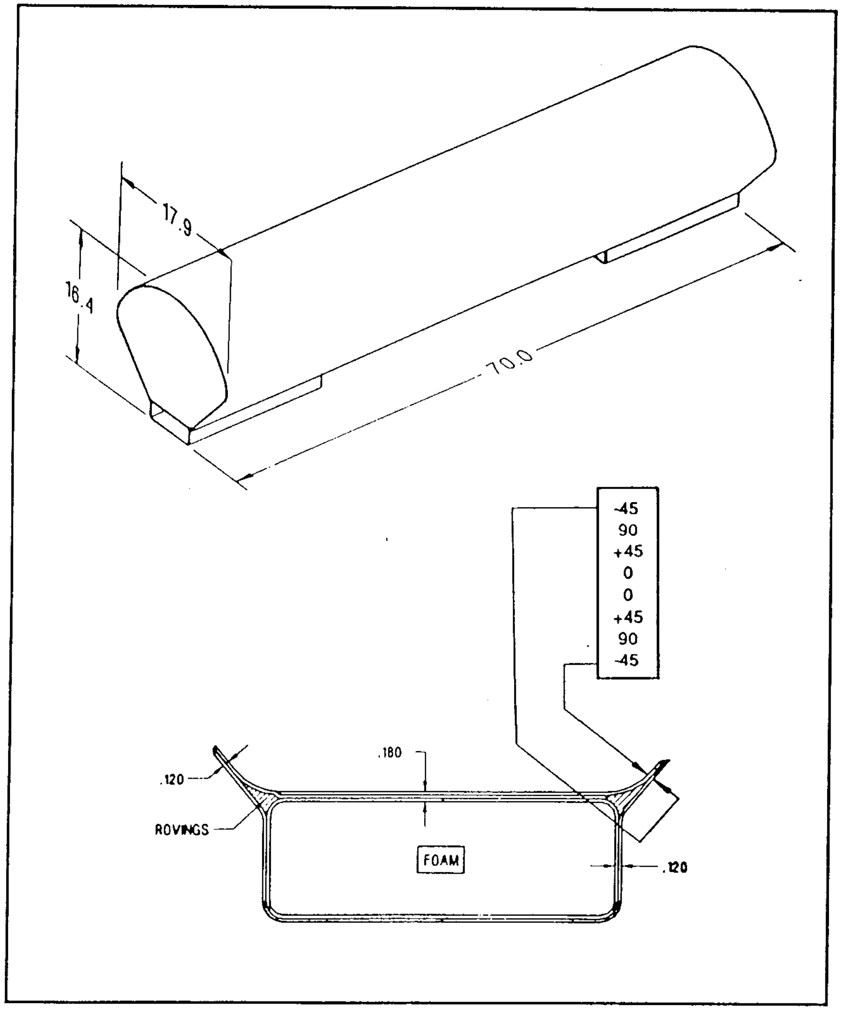
7B - INJECT RESIN USING A PRESSURE POT

RTM FIN "LESSONS LEARNED"



- STITCHED MATERIAL GREATLY REDUCES PLY LAY UP TIME
- PROCESSING OF NEW EPOXY RESIN SYSTEM IS MORE REPEATIBLE
- BMI RESIN SYSTEM NOT AS SENSITIVE TO PROCESSING TEMPERATURE AS ORIGINALLY ANTICIPATED
- ROHACELL FOAM CANNOT WITHSTAND UNSUPPORTED POST CURE AT 490°F

RESIN TRANSFER MOLDED DISPENSER TUBE



MATERIALS:

E-GLASS/EPOXY (STITCHED)

CARBON/EPOXY (STITCHED)

FABRICATOR:

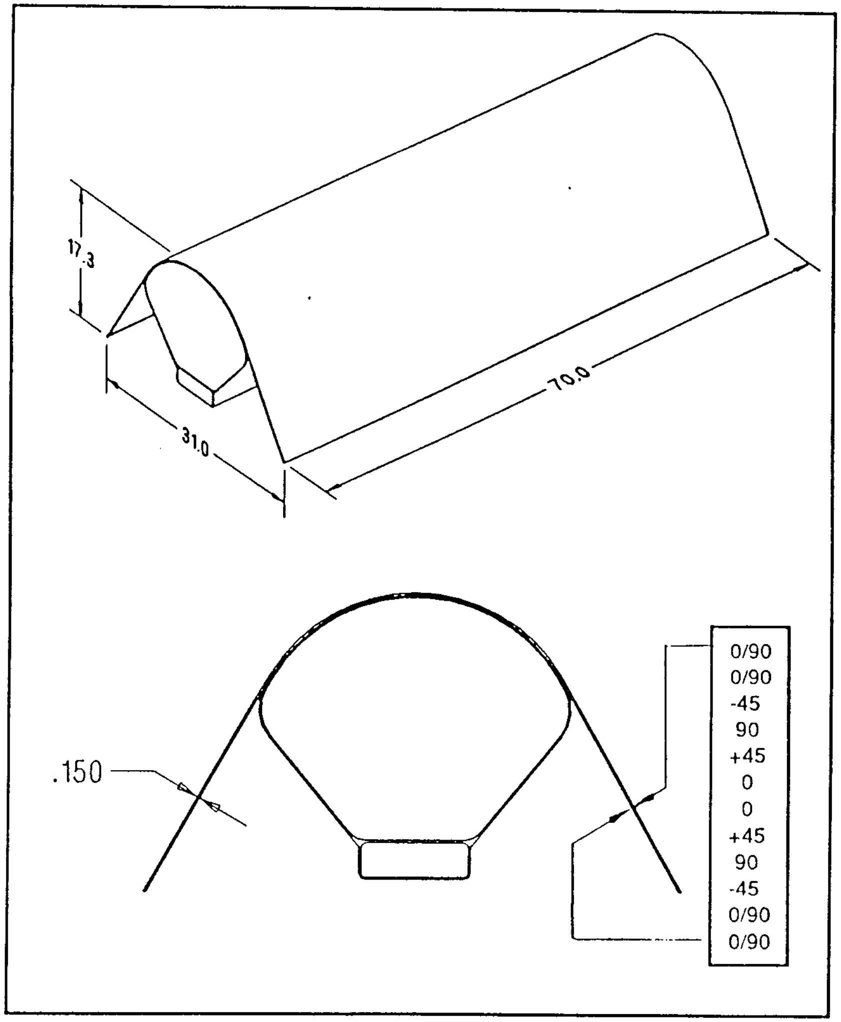
DESIGN EVOLUTION 4

SUPPLIERS:

HEXCEL/HITECH

SHELL CHEMICAL CO.

RESIN TRANSFER MOLDED JOINING DEMO



MATERIALS:

E-GLASS/EPOXY (STITCHED)

CARBON/EPOXY (STITCHED)

FABRICATOR:

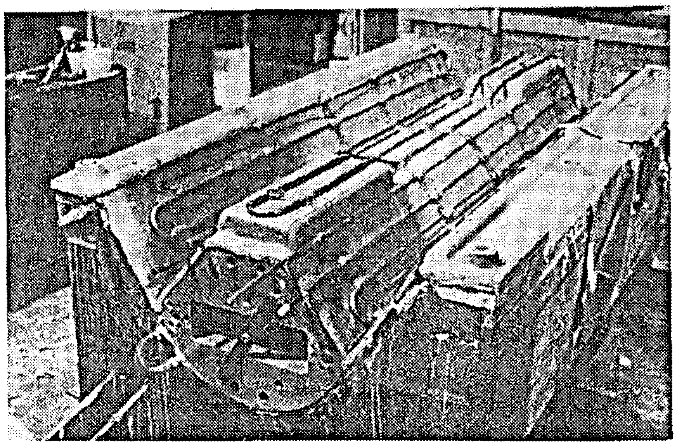
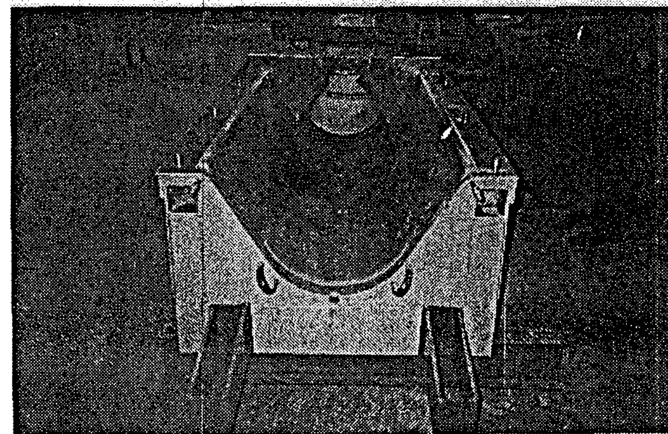
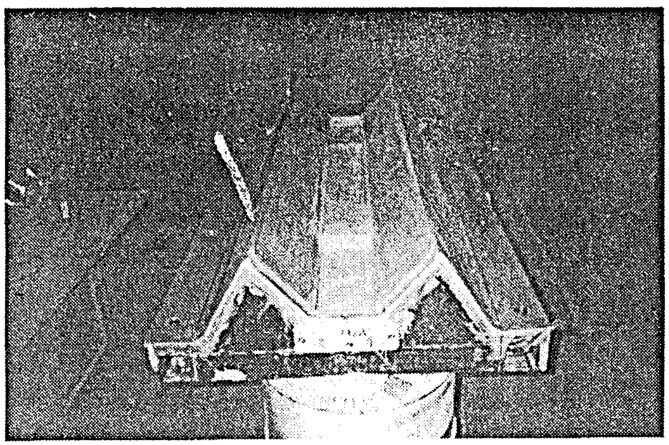
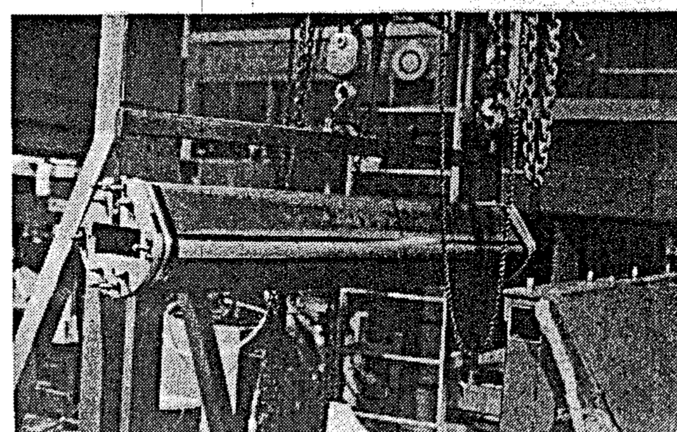
DESIGN EVOLUTION 4

SUPPLIERS:

HEXCEL/HITECH

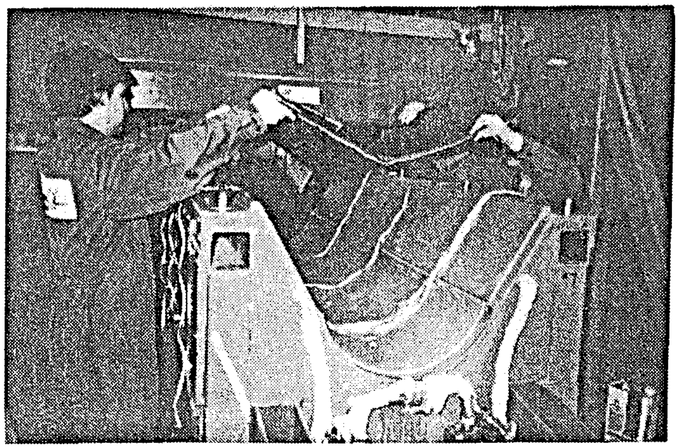
SHELL CHEMICAL CO.

RTM DISPENSER TUBE & JOINING DEMO TOOLING

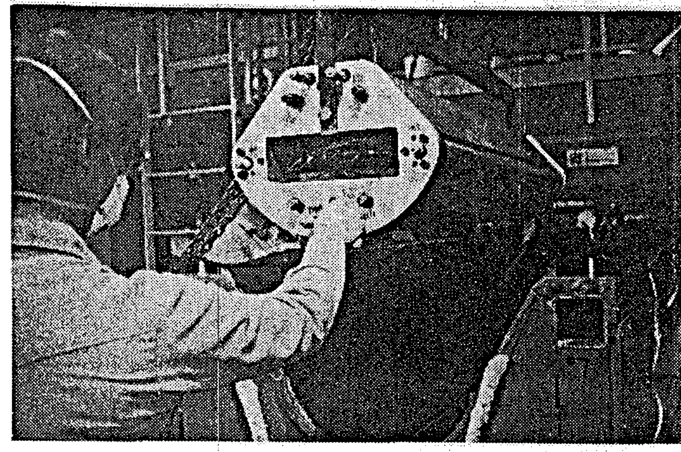





A three piece, integrally heated composite tool with a collapsible mandrel was used.

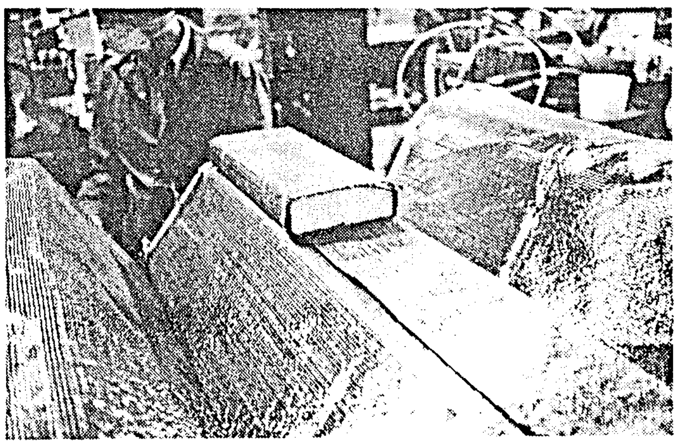
RTM DISPENSER TUBE FABRICATION



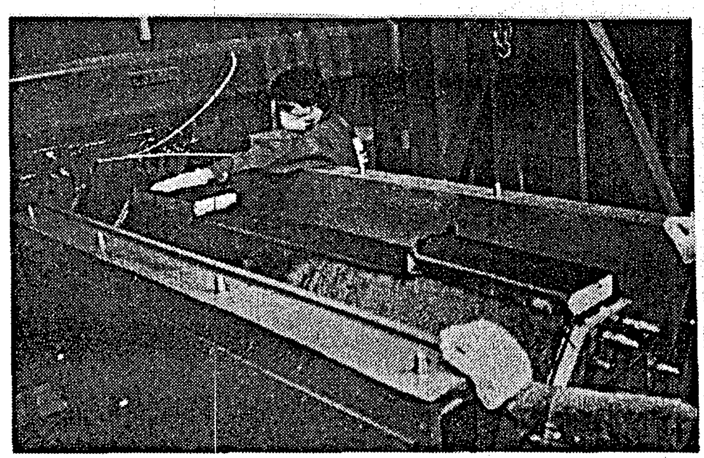
1-PLACE MATERIAL IN MOLD



2-MOVE MANDREL INTO POSITION

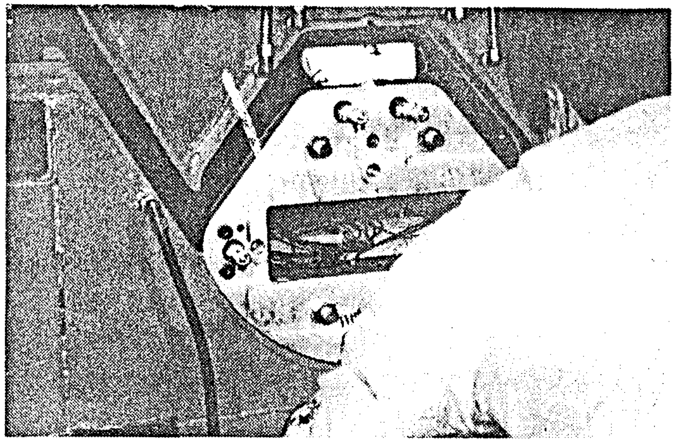


3-INNER PLIES ARE IN POSITION

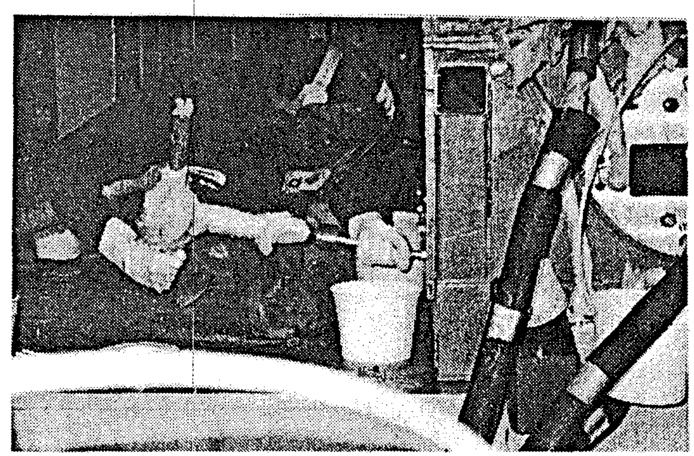


4-TUBE IS READY FOR INJECTION

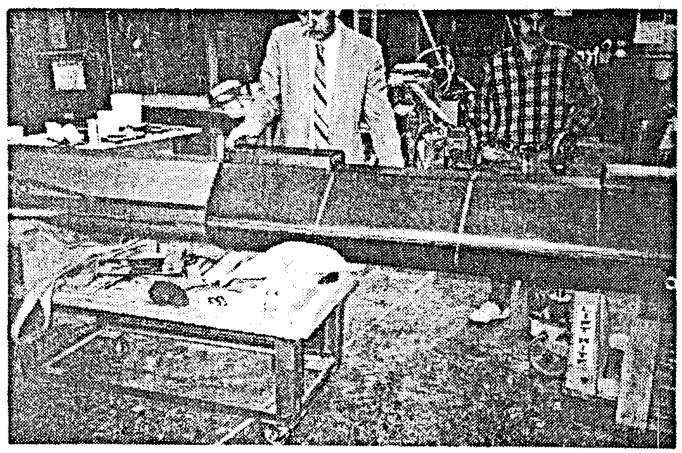
RTM DISPENSER TUBE FABRICATION (continued)



5- CLOSE THE MOLD

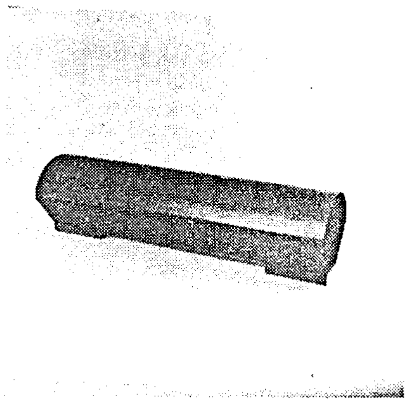


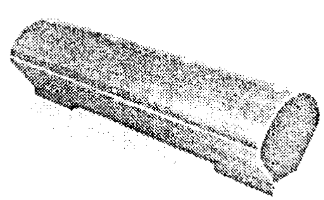
6-INJECT THE RESIN



7- REMOVE MANDREL

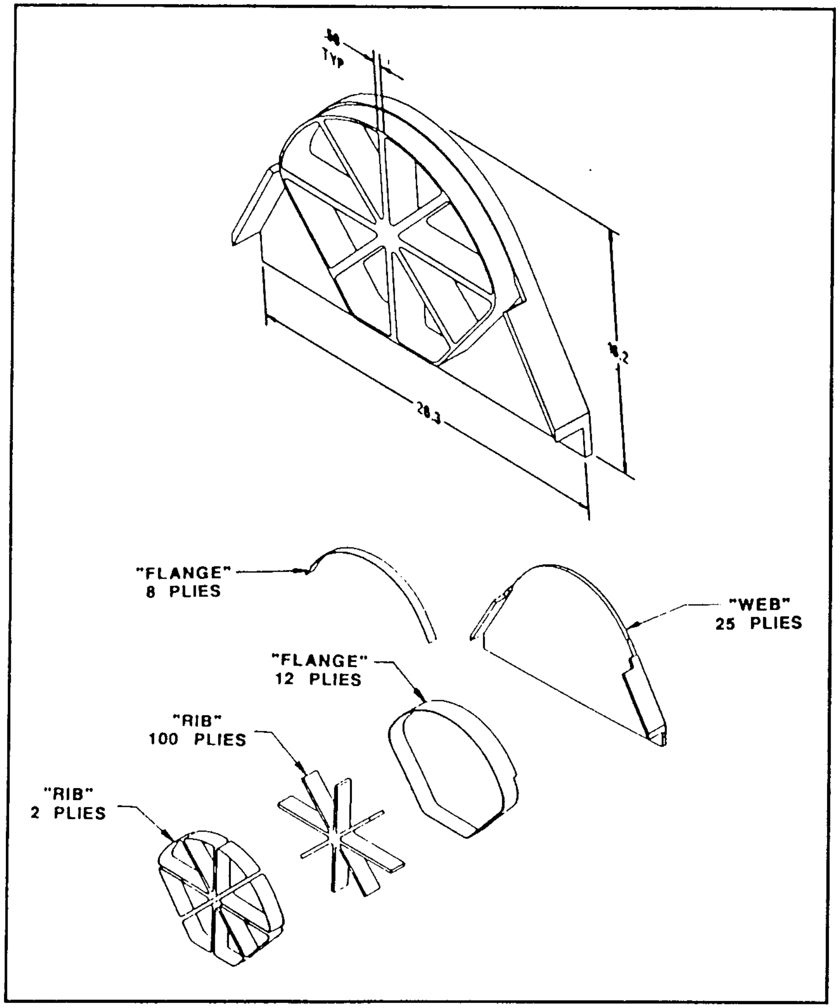
RTM DISPENSER TUBE "LESSONS LEARNED"





- COLLAPSIBLE MANDREL NEEDS TO BE STIFFER TO PREVENT DEFLECTION
- MINIMIZE DISSIMILAR TOOLING MATERIALS TO PREVENT CTE MISMATCHES
- PULL VENTS OUT PRIOR TO RESIN GELATION TO MINIMIZE VENT DRILLING TIMES
- THERE ARE DURABILITY CONCERNS WITH COMPOSITE TOOLING

RESIN TRANSFER MOLDED BULKHEAD



MATERIALS:

E-GLASS/EPOXY (PREFORM)
CARBON/EPOXY (PREFORM)

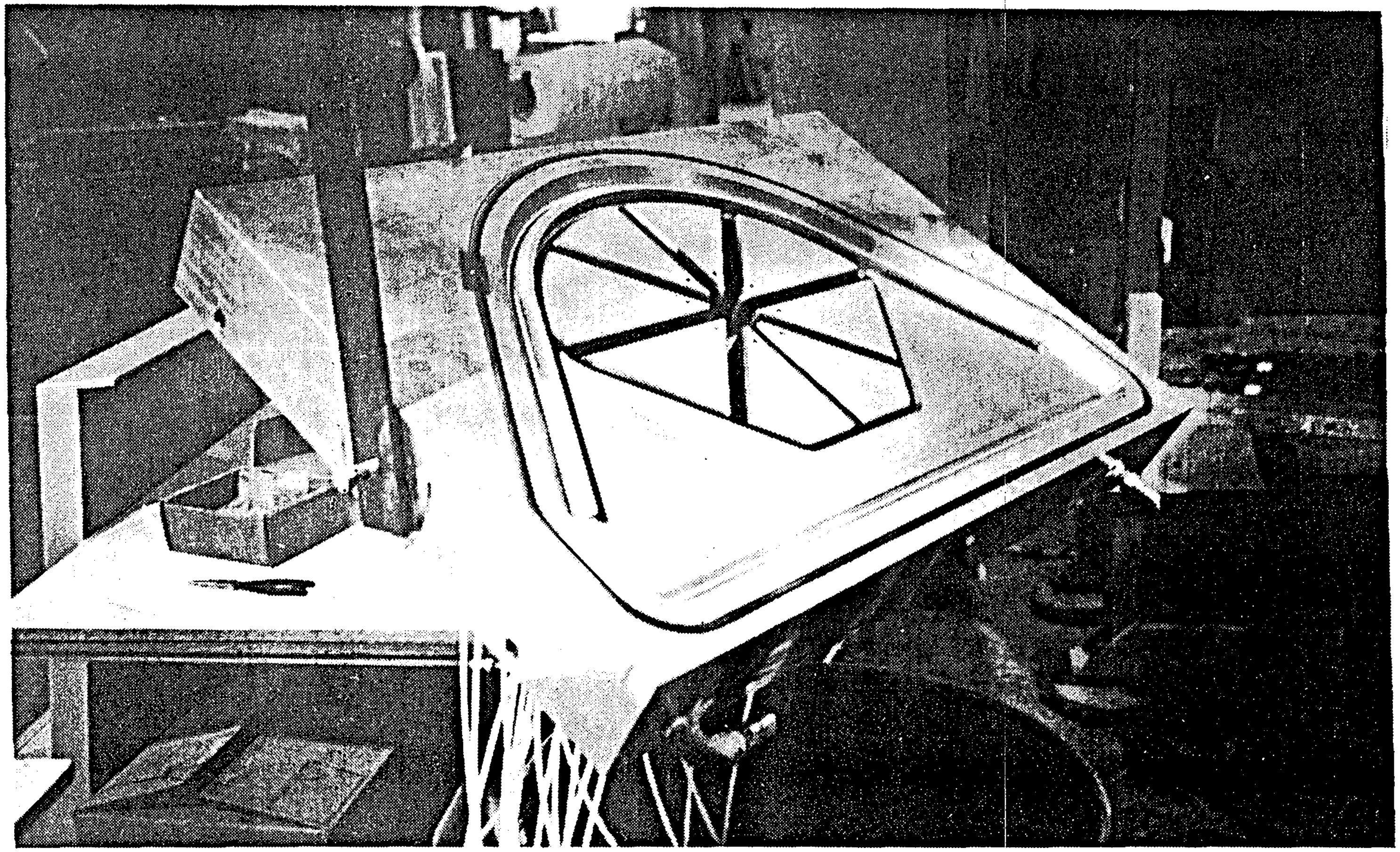
FABRICATOR:

DESIGN EVOLUTION 4

SUPPLIERS:

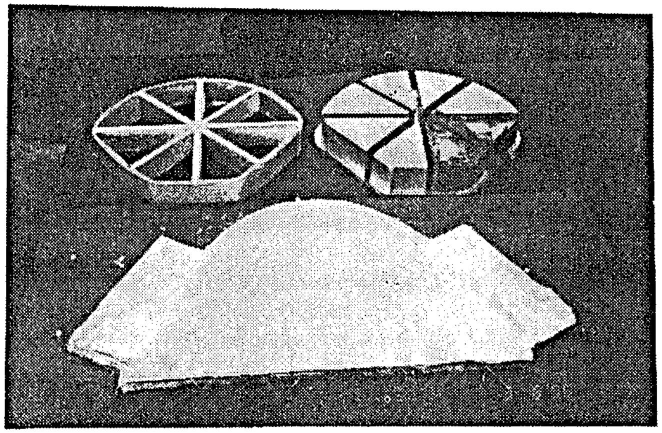
HEXCEL/HITECH
SHELL CHEMICAL CO.

RTM BULKHEAD TOOLING

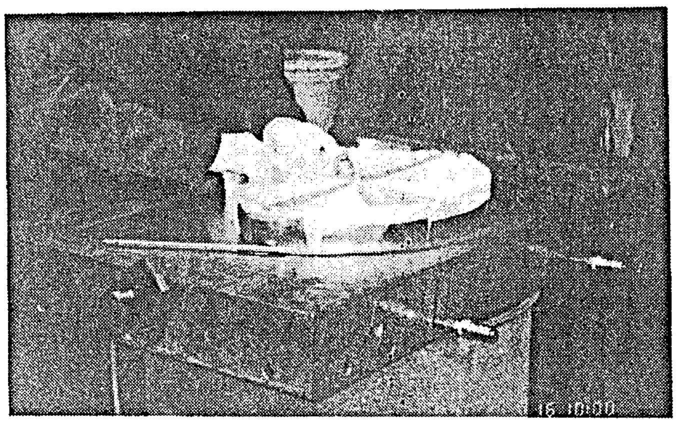


The integral heated aluminum tool has a moat gate and multiple vents for air removal.

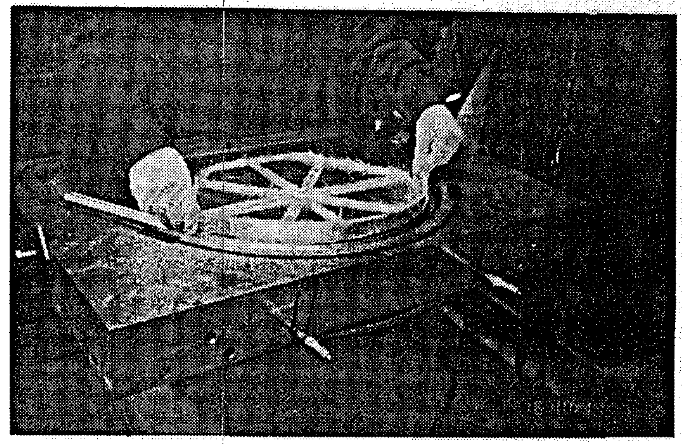
RTM BULKHEAD FABRICATION



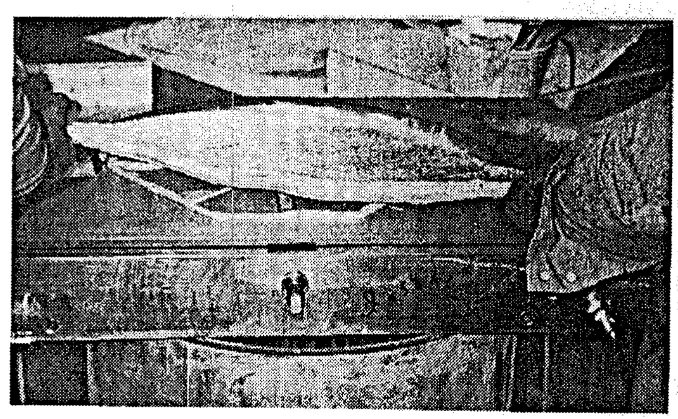
1- GLASS PREFORM



2- PLACE SPOKES IN MOLD

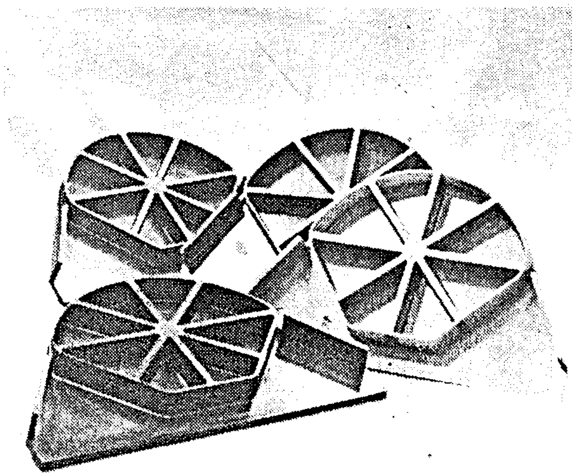


3- PLACE UPPER STRIP IN MOLD



4- PLACE WEB ONTO SPOKE, CLOSE MOLD, INJECT, AND CURE

RTM BULKHEAD "LESSONS LEARNED"



- REDUCE NUMBER OF SPOKES TO SIMPLIFY PREFORM DESIGN
- INCORPORATE TOOL EJECTOR SYSTEM TO EASE PART REMOVAL
- MINIMIZE THE NUMBER OF VENTS TO DECREASE TOOL PREPARATION TIME
- IMPROVE TOLERANCE CONTROL OF PREFORM FOR BETTER FIT IN MOLD

Suggested R&D Directions

Preforms

- Reduce Cost
- Improve tolerance control
- Trade-off preform complexity versus ply layup time

Resin Systems

- Optimize resins for RTM
- Evaluate high temperature resins
- Evaluate binders
- Improve durability of release agents

Tooling

- Standardize gating and venting concepts
- Develop resin flow models
- Reduce "trial and error" design

Processing Equipment

- Evaluate sensors
- Incorporate in-process controls

TEXAS INSTRUMENTS
ANTENNA/NONMETALLICS DEPARTMENT

INSTITUTE FOR DEFENSE ANALYSIS
CLOSED MOLD MANUFACTURING
MAY 15-16, 1995

RTM COST REDUCTION

GRAY FOWLER
214-952-2796

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RTM COST REDUCTION

AGENDA

ANTENNA/NONMETALLICS DEPT. OVERVIEW

TOOLING

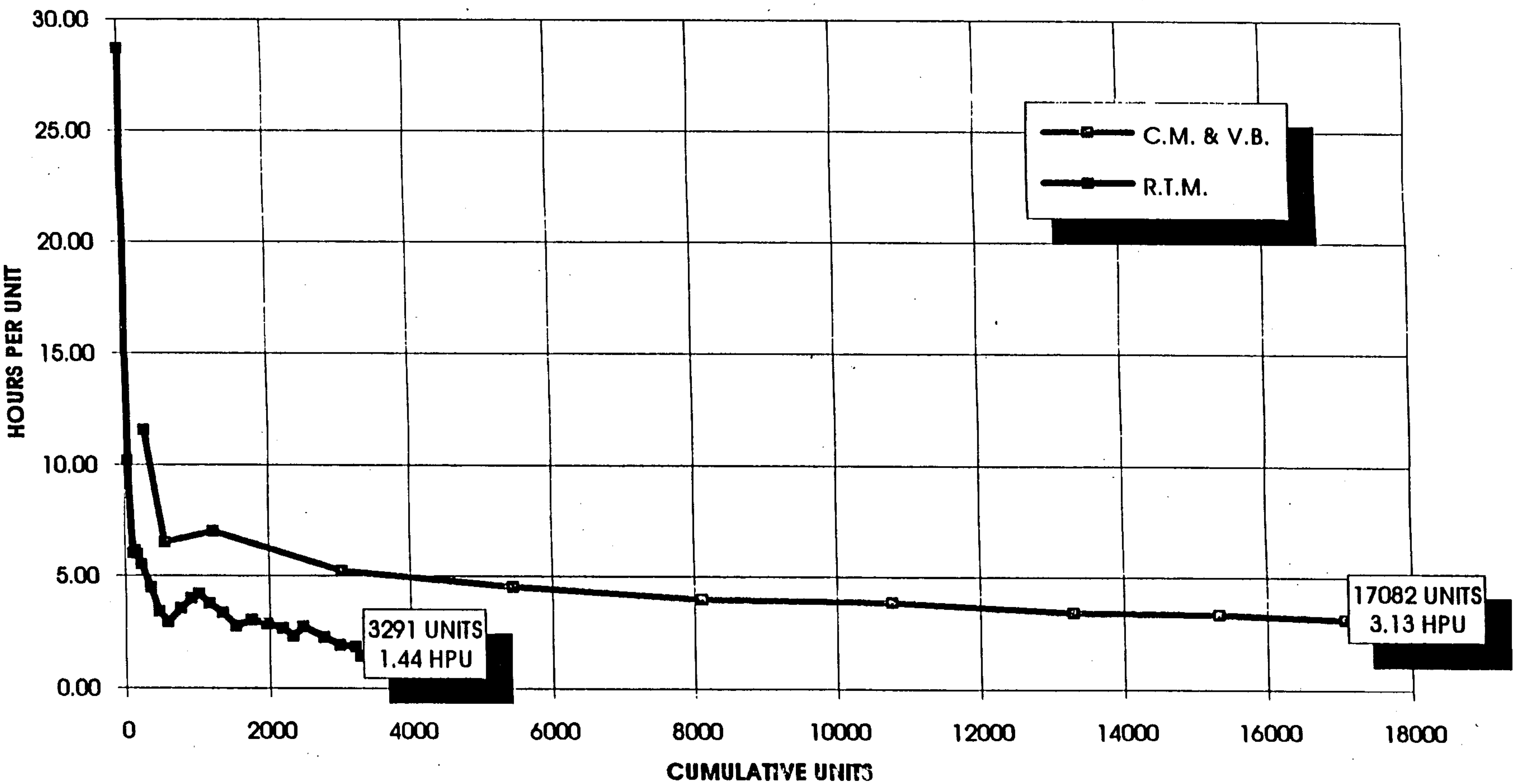
- Prototype Tooling
- Production Tooling
- Near Net Tooling

MATERIALS

PRODUCTION

- Cycle Time
- Statistical Process Control

RESIN TRANSFER MOLDING VS. COMPRESSION MOLDING & VACUUM BAG PROCESSING
HARM PRODUCTION



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PROTOTYPE TOOLING

STEEL
- Excellent durability
- High machining cost
- High modulus

ALUMINUM
- Low durability
- Moderate machining cost
- Moderate modulus

ALUMINUM-HARD ANODIZED
- Good durability
- Moderate machining cost
- Moderate modulus

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PROTOTYPE TOOLING (Continued)

SLA-CAST ALUMINUM (Hard anodize)
- Lower machining cost
- Good durability
- Moderate modulus

SLA-ALUMINUM-COMPOSITE
- Lowest machining cost
- Low durability
- Moderate-low modulus

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PRODUCTION TOOLING

STEEL TREATMENTS
- Ion Nitride surface hardening (P-20)
- Through Hardening (A-6, D-2, 440)

QC CERTIFICATION
- Individual Certified molds
- Certified preform fabrication tools
- Operator self inspection certification

LOW VOLUME PRODUCTION
- Hard anodized aluminum
- Non hardened steel

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NEAR NET TOOLING

FLATPLATED FEATURES
- Holes
- Bosses
- Countersinks
- Square holes
- Hat Stiffener
- Rib Stiffener

FUTURE CONSIDERATIONS
- SLA-Cast Al-Composite Near net tooling
- Expand net molded inserts and stiffeners
- Fastening/joining
- Sandy Munro concepts

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MATERIALS

HIGH PERFORMANCE
- Tg>250°C
- Water absorption <.5%
- Resin blend = $20-25/lb

MID PERFORMANCE
- Tg up to 125°C
- Water absorption <1.0%
- Resin blend = $3-4/lb

DATA
- Relief of B-Basis allowables
- Creation of a Tri-Service material data base

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PRODUCTION CYCLE TIME

PURPOSE

- Cost reduction
  1. WIP reduction
  2. Less tooling required
  3. HPU reduction

PERFORMING

- Die-cutting & other cutting
- Drapable fabric vs. strength
- Braid properties

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PRODUCTION CYCLE TIME (Continued)

SNAP CURING

- Advantages
  1. Cycle time
  2. Labor reduction

PROCESS CONTROLS

- Programmed process/part feedback

- In-Situ Monitoring
  1. Pregpreg (TI/NCMS polyimide)
  2. RTM Airframe
  3. RTM Missile-non value added

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PRODUCTION TQM

SIX SIGMA ANALYSIS
- Design
- Production metrics

AUTOMATIC PROCESS LOGGING
- Controller Interface

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RTM COST REDUCTION

BARRIERS FOR FUTURE COST REDUCTIONS

PROTOTYPE TOOLING
- Investigate alternatives to steel to reduce NRE and delivery time

LOW VOLUME PRODUCTION TOOLING
- Determine tool durability to make RTM cost effective at lower volumes

NEAR NET TOOLING
- Reduces or eliminate machining
- Reduces part count by consolidation
- Reduces bonding/fastening operations

FASTENING-JOINING-BONDING
- Testing of innovative joint designs
- Investigate joining methods to eliminate mechanical fasteners

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RTM COST REDUCTION

SUMMARY

MATERIAL CHARACTERIZATION

- Relief of B-Basis Allowables
  1. NRE reduction
- Creation of a Tri-Service materials data base
  1. More materials available
  2. NRE reduction
- Utilize high performance (high cost) materials only when needed

PERFORMING TECHNIQUES

- Investigate improved fabrication methods
  1. Reduces most labor intense component of the RTM process

Workshop on Closed-Mold Manufacturing of High Performance Composite Missile Structures

by

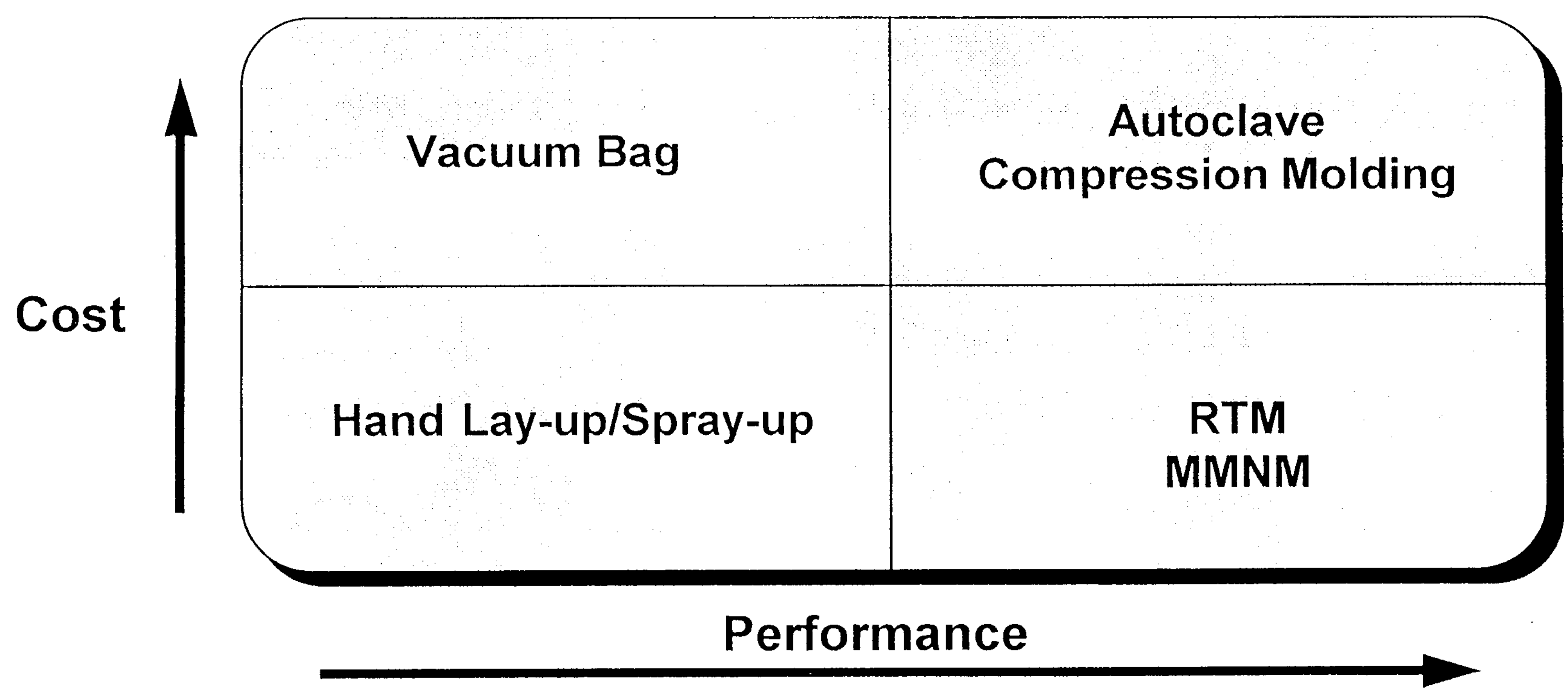
Gerald Sutton, Director
RTM Product Development
INTELLITEC
a Division of TPG, Inc.

May 15-16, 1995

Agenda

- Why Closed Mold Processes
- Cost Drivers
- RTM Elements
- Factors Effecting Difficulties of RTM
- New Materials Wish List
- Lessons Learned
- Summary

Why Closed Mold Processes?



The Goal..........to Achieve Equivalent Performance at 50% Less Cost

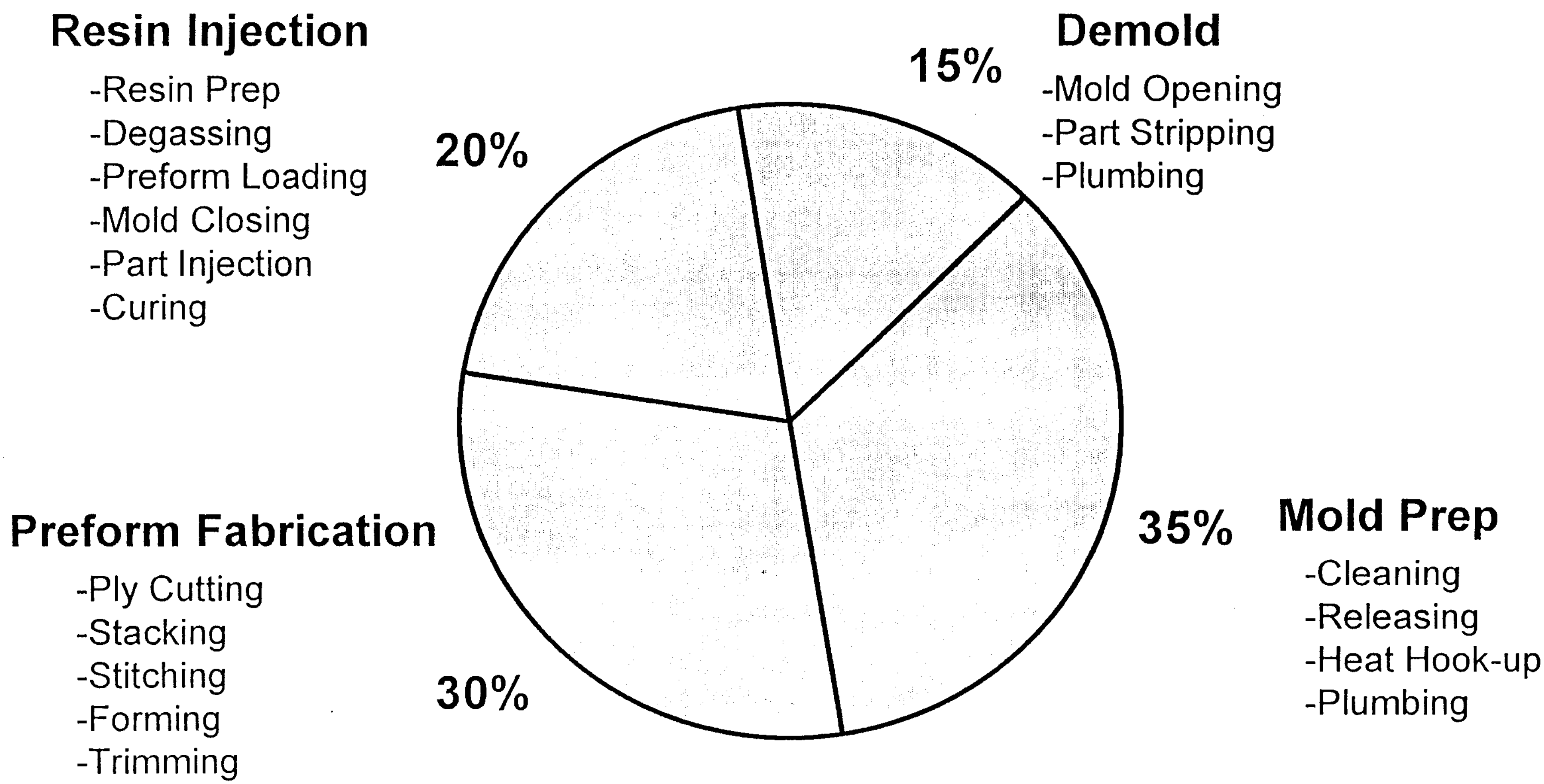
Closed Mold Process Implementation

What makes it attractive?
- -Better dimensional control
- -Preforming done off-line
- -Net molding
- -Low emissions

What makes it cost effective?
- -Part consolidation
- -Lower raw material cost
- -Multiple cycles and cavities
- -Self contained operations
- -Assembly control
- -Automation potential

What puts it in production?
- -Cost
- -Cost
- -Cost

Primary Labor Cost Drivers for RTM Processing



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Elements of RTM

A Critical Checklist

Tooling

- Complete Seal
- Temperature Control
- Resin Flow
- Dimensions

Preforms

- Fiber Volume
- Fiber Orientation
- Fiber Bulk
- Net Molding

Resins

- Viscosity
- Pot Life
- Cost

Processing

- Controllability
- Repeatability
- Predictability

To Successful Molding

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RTM Resin Systems

Shell DPL 862/W
Dow 123/H41
Vinyl Esters

250^0 F
$1.50 to $3.00/pound

3M-PR500
CIBA RTM 6
Shell 9405-9470
Cynate Esters
Fiberite 977-3

350^0 F
$12.00 to $80.00/pound

Shell 65 FWR BMI
BASF 5250-4 RTM BMI
BP V-390RTM BMI
Ciba 89-101 BMI

450^0 F
$40.00 to $65.00/pound

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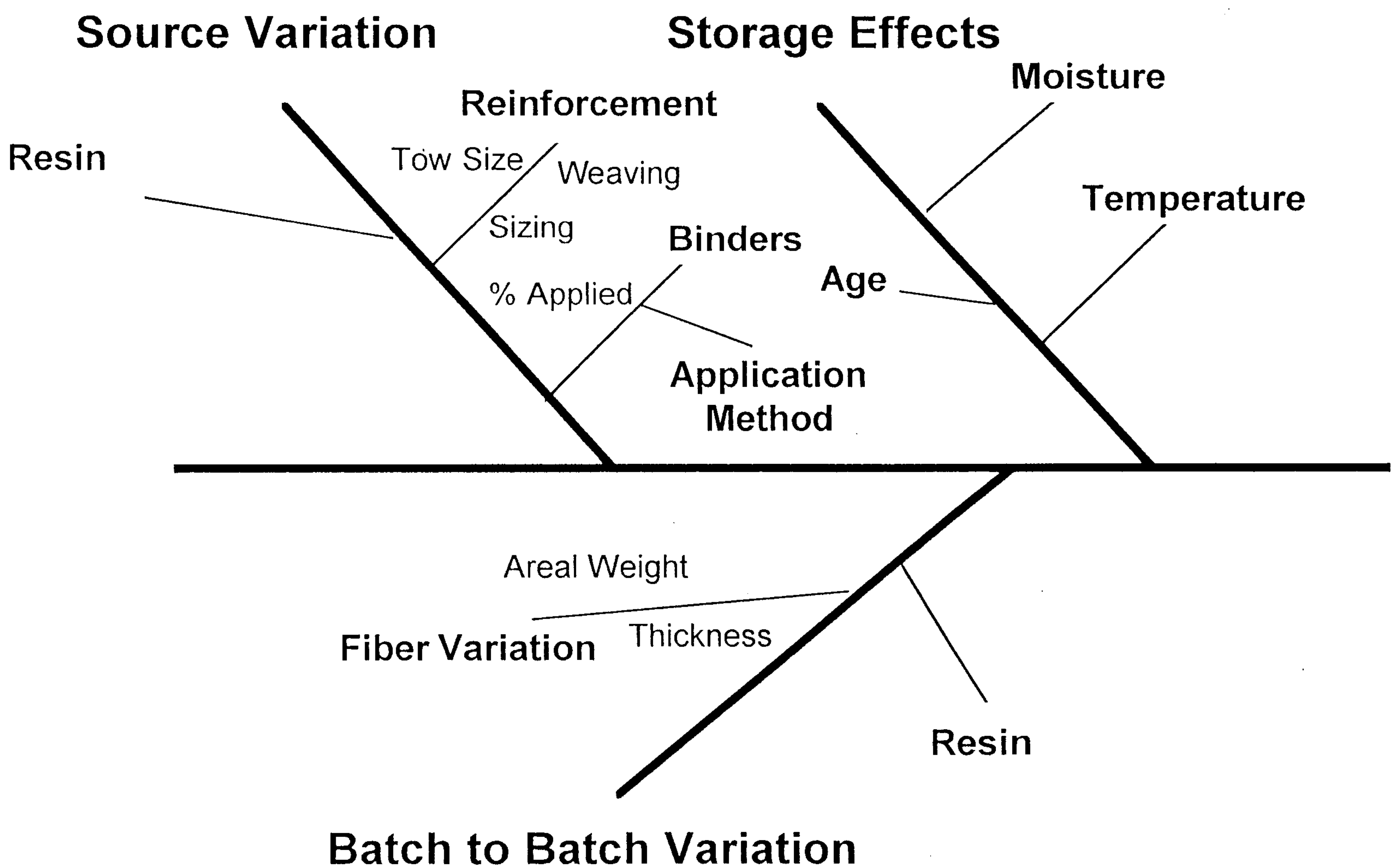
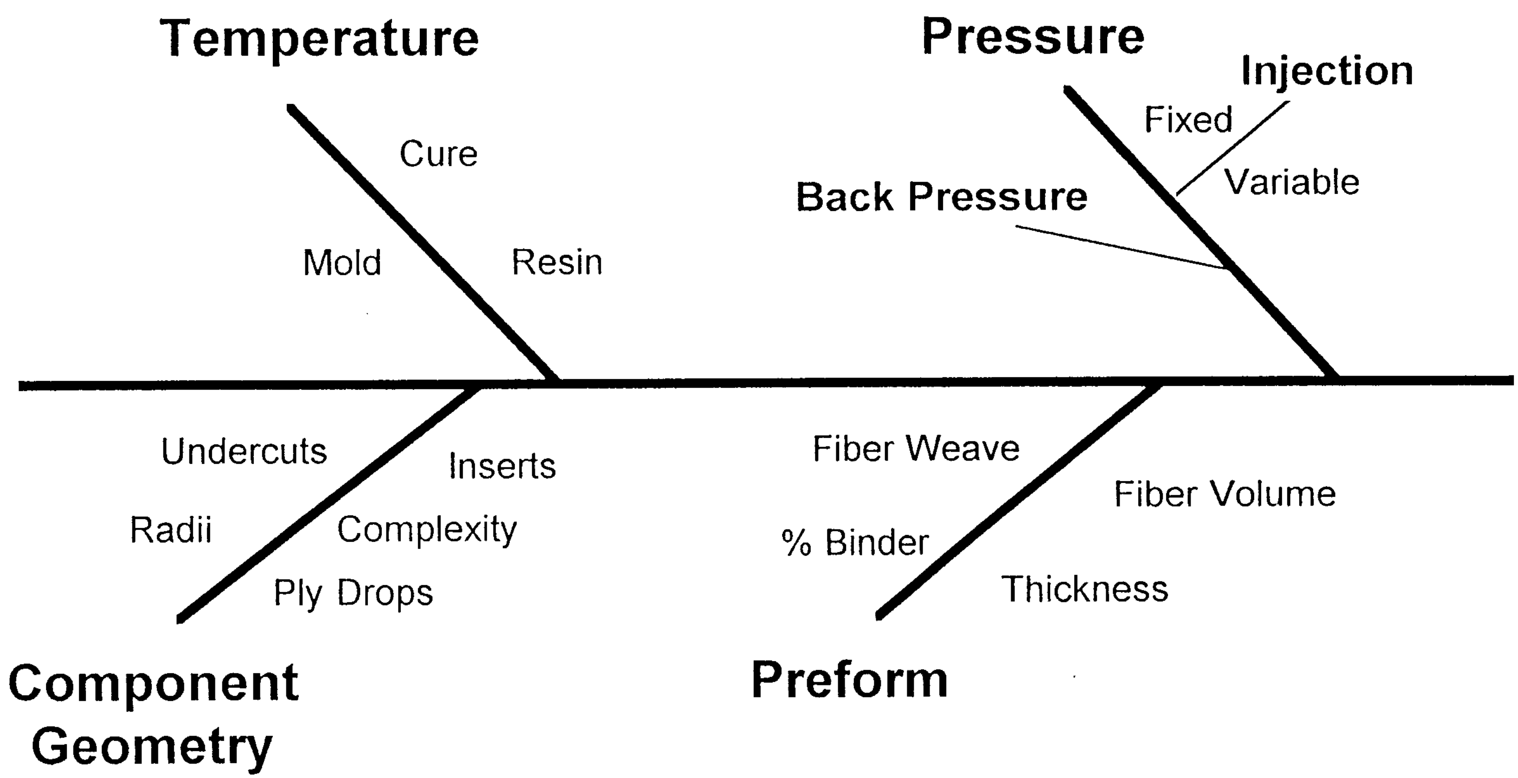
Factors Effecting RTM Raw Materials



Factors Effecting RTM Processing



New Materials Wish List

Resins

- High Performance/Low cost
- Low Viscosity
- Long Pot Life
- Single Component System

Reinforcements

- Conformable Fabrics
- Lower Cost Value Added Weaving (2D &3D)
- Binder Application Enhancements

Lessons Learned

Designing to Fiber Volume:

Closed Molding is a fixed thickness process requiring:

- Fiber Volume Control
- Material Density (Areal Weight) Control
- Balance of the Laminate

Optimizing the Attributes of RTM:

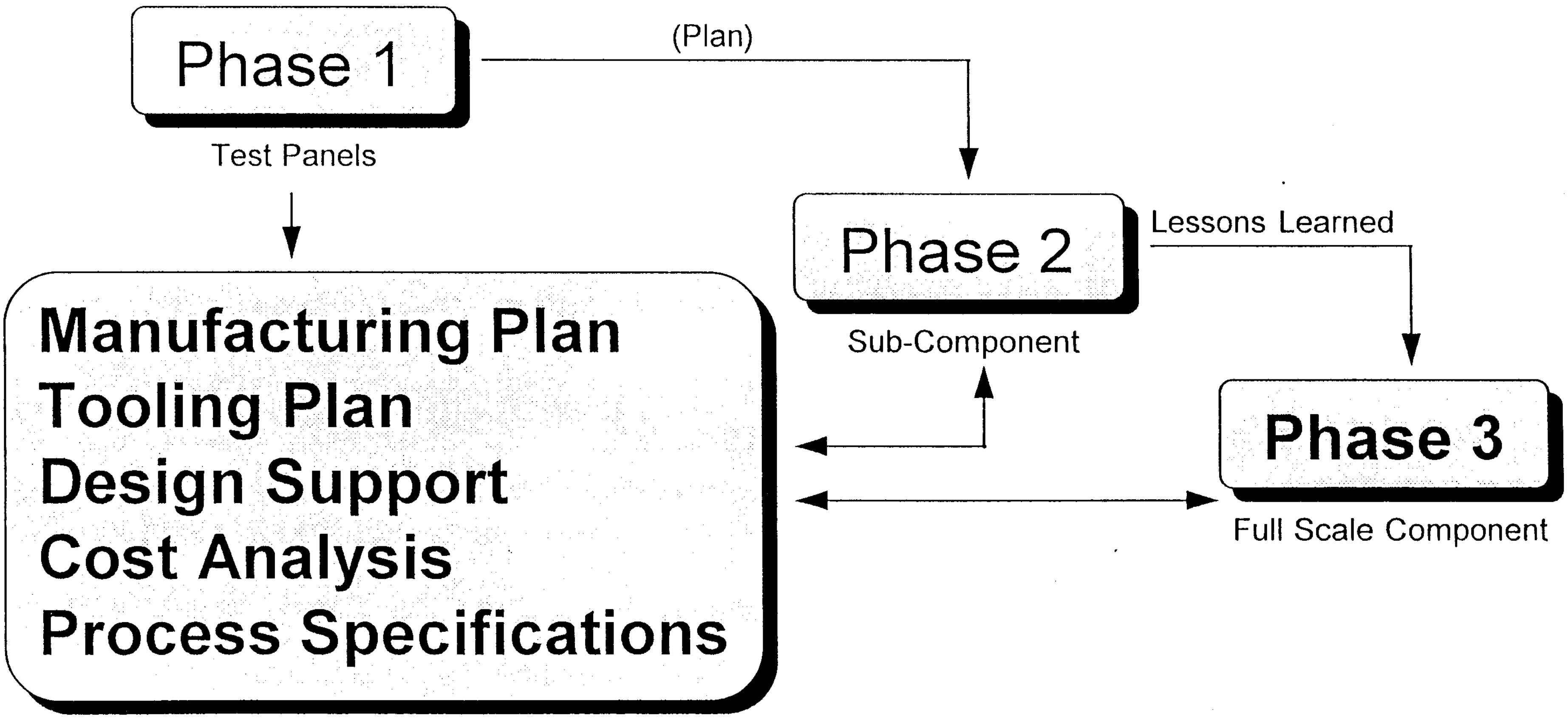
Choices/Combinations of Fiber Architecture

Choices of Resins

Choices/Combinations of Tooling Materials

Flexible Manufacturing Approach for Cost Control

Typical RTM Technology Implementation Plan



Summary

- RTM is gaining in acceptance within the composite industry
  - More Applications
  - More Successes
- Work Continues to Develop the Process to it's fullest capability
- Volume Increases are helping the cost cause
- New Materials are solving some problems
- More Data is still needed to continue the process acceptance

COMPOSITES HORIZONS, INC.

Matched Metal Net Shaped Molding of the F-16, PW-229 Engine Exhaust Flap

Milton Anderson
Composites Horizons Inc.

May 15, 1995

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F100-PW-229 ENGINE EXHAUST FLAP

Customer: Pratt & Whitney Aircraft
Program: F100 PW-229, F-16 Engine
Material: PMR-15/Graphite Polyimide
600°F Use Temp

Tooling: Steel Compression Mold
CAREMOLD Wash Out Ribs

COMPOSITES HORIZONS, INC.

F-16 Engine Exhaust Flap

Replaced titanium assembly
15 Flaps per engine
PMR-15/ Carbon Fiber Prepreg
40 plies 8 HS Woven, 20 plies UD tape
Titanium Hinge
Composite Bushing
500° F continuous use temp
Co-cured, NAK-55 steel compression Mold
Production quantity 1,000 + units

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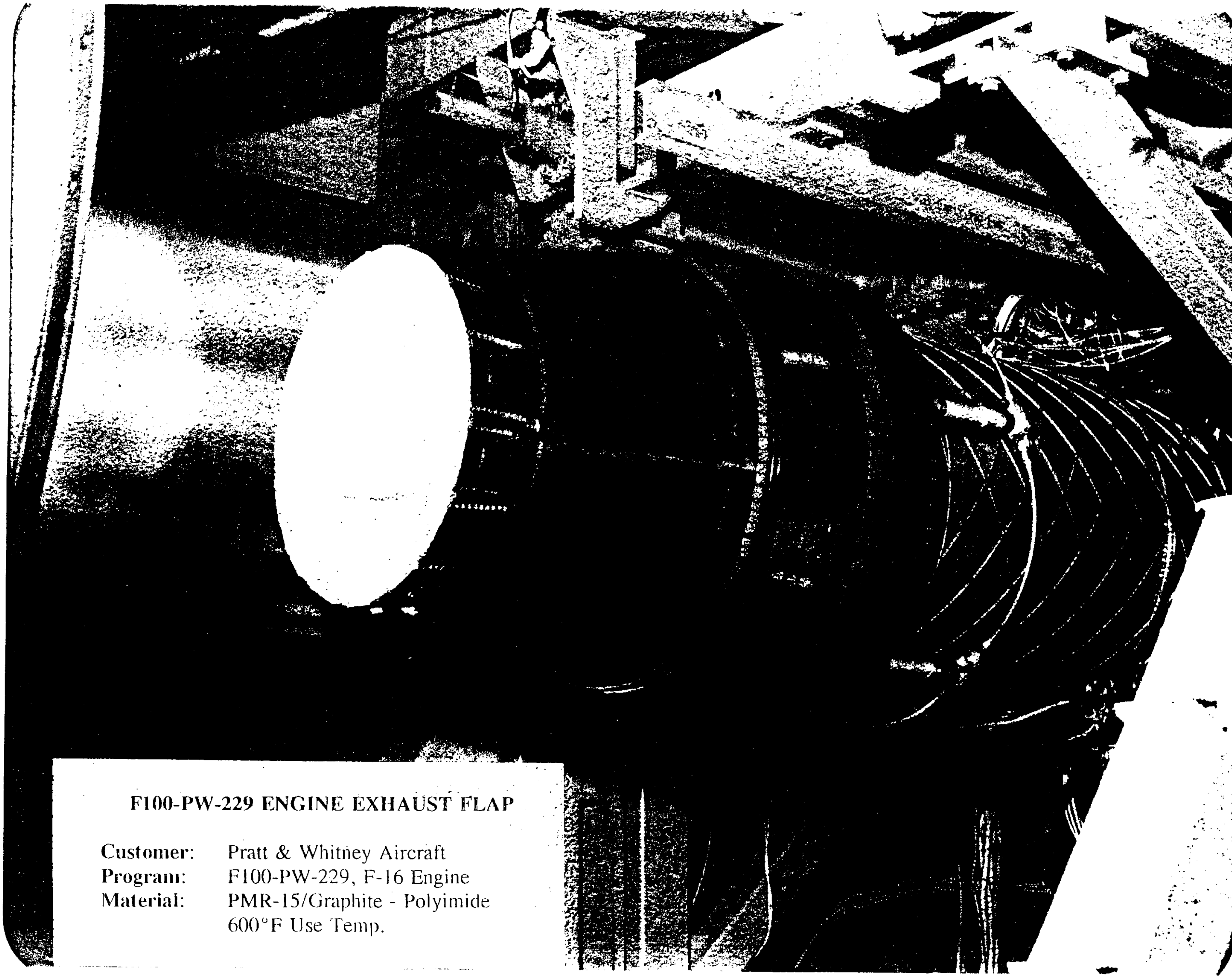

F100-PW-229 ENGINE EXHAUST FLAP

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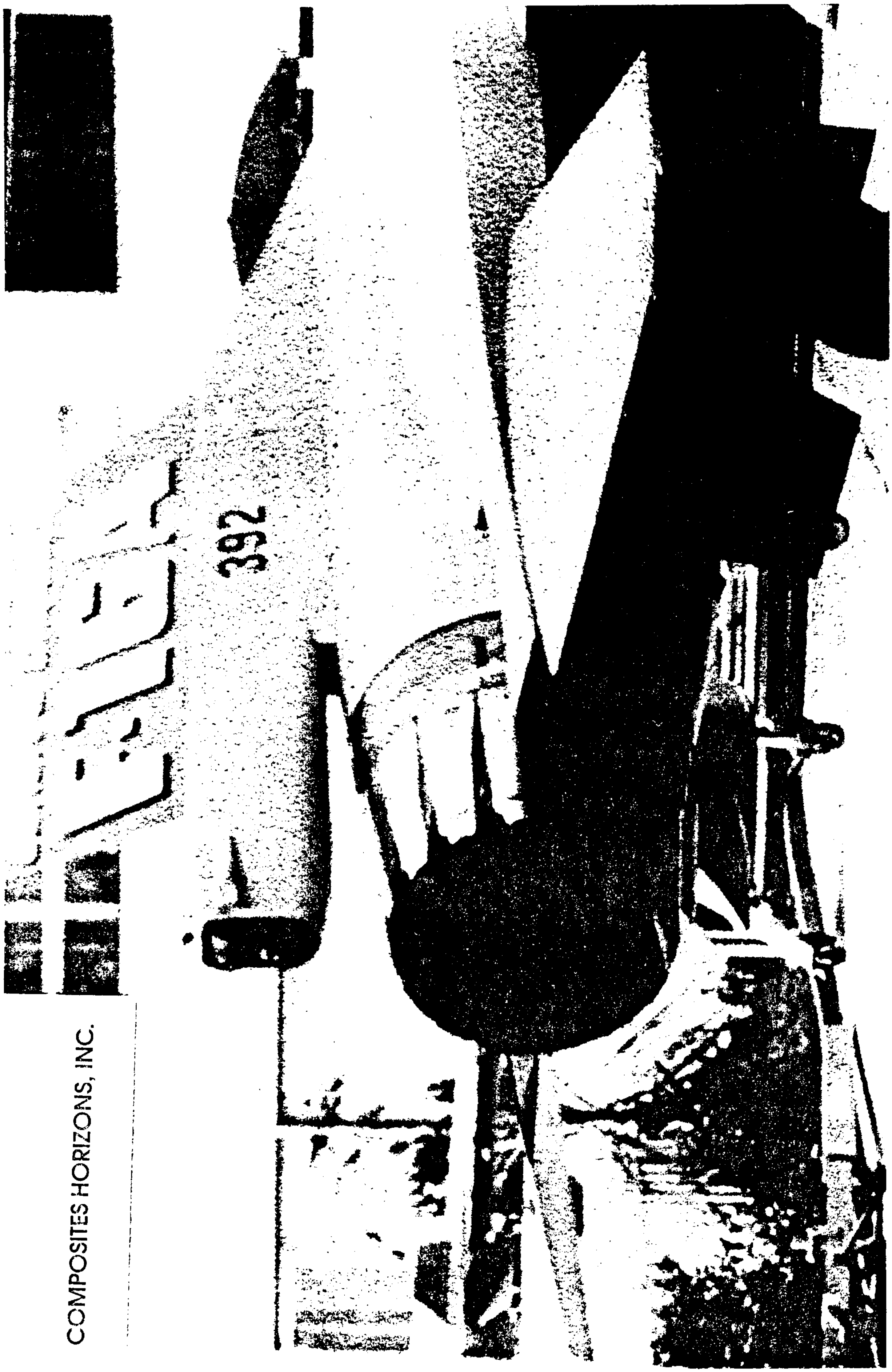
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Fabrication Approach

Steel rule die cutting
Caremold mandrel casting
Hand lay-up
2 Part Imidization
Optimized compression mold cycle
Free standing post cure
Waterjet EOP trim
Caremold wash-out
Sonic inspection

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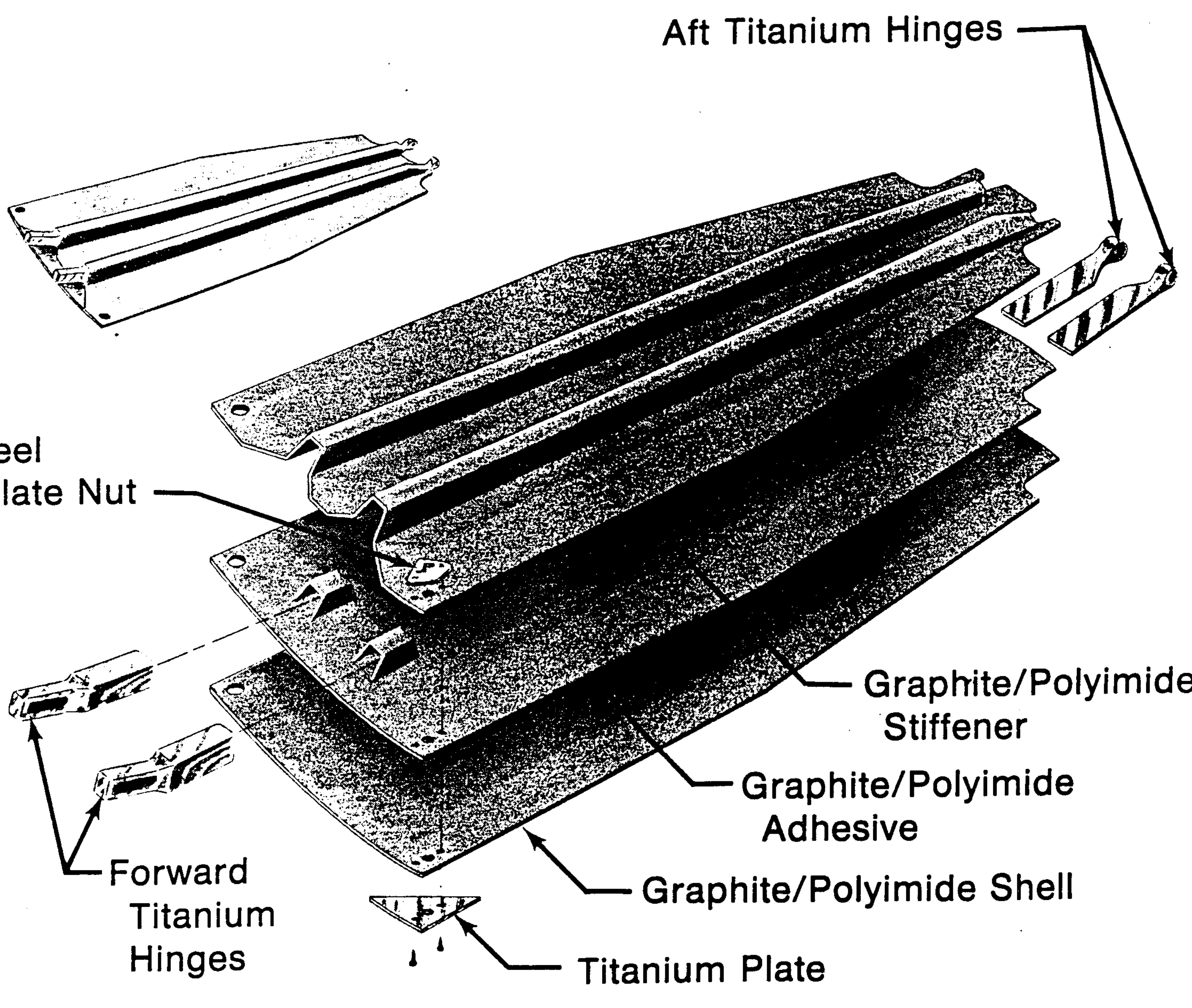

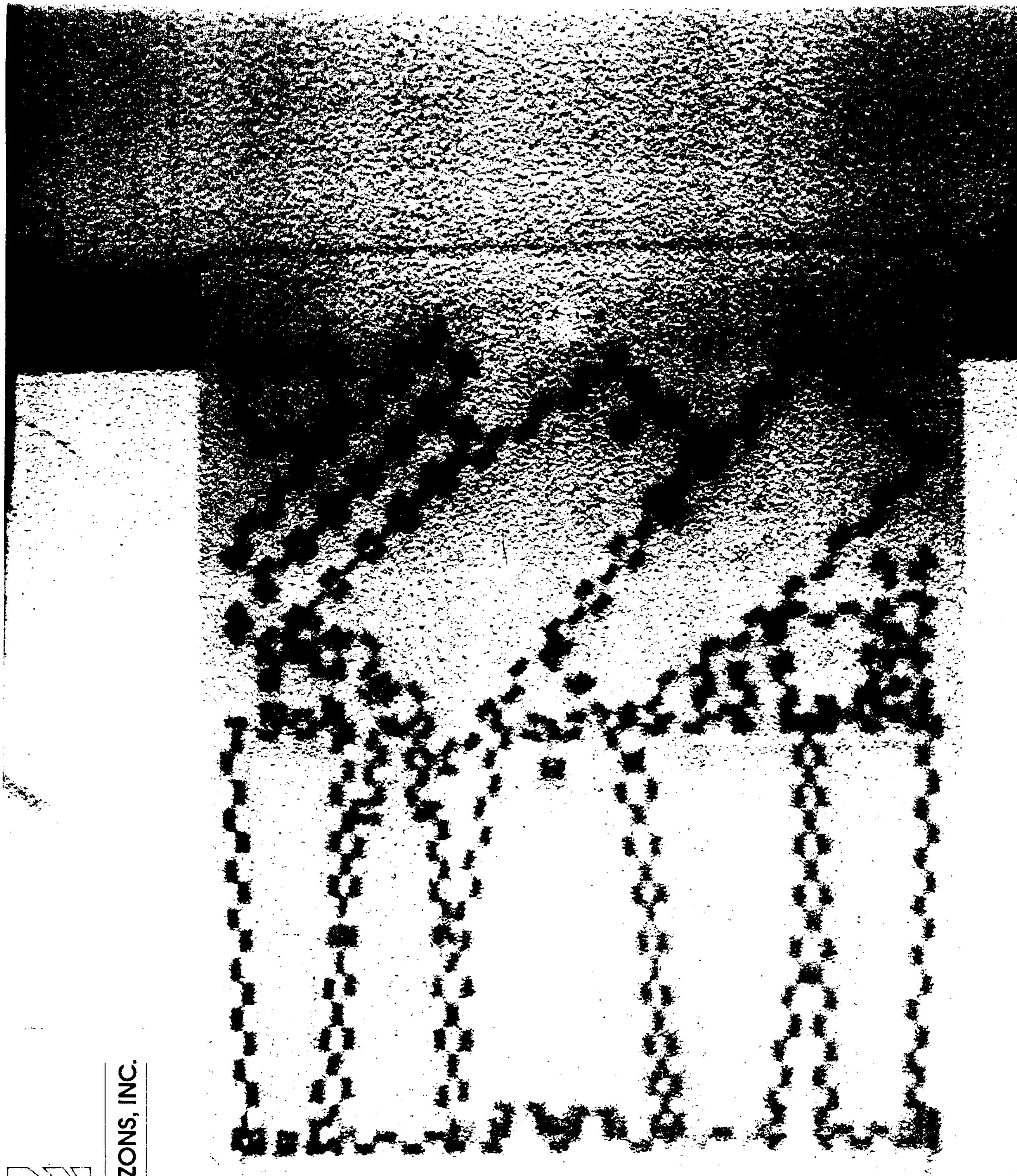

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Problem Areas

1.0 Co-cured/hollow closeout cavity
2.0 100% bulk factor of Imidized PMR-15
3.0 CTE differential to 600° F
4.0 8 hour standard PMR-15 cure cycle

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1.0 Co-Cured/Hollow Closeout Cavity

Problem: Secondary bonding creates a problem because of unreliable adhesives for 600° F use.

3/8" diameter bushing hole in 1" square hat section prevented solid tooling removal.

Solution: Caremold castable tooling

Dry Powder mix with water
Cast at room temperature
1 hr room temperature dry
6 hr, 600° F bake
Withstand 800° F, 1,000 PSI.
CTE same as CF/PMR-15
Washes out with water

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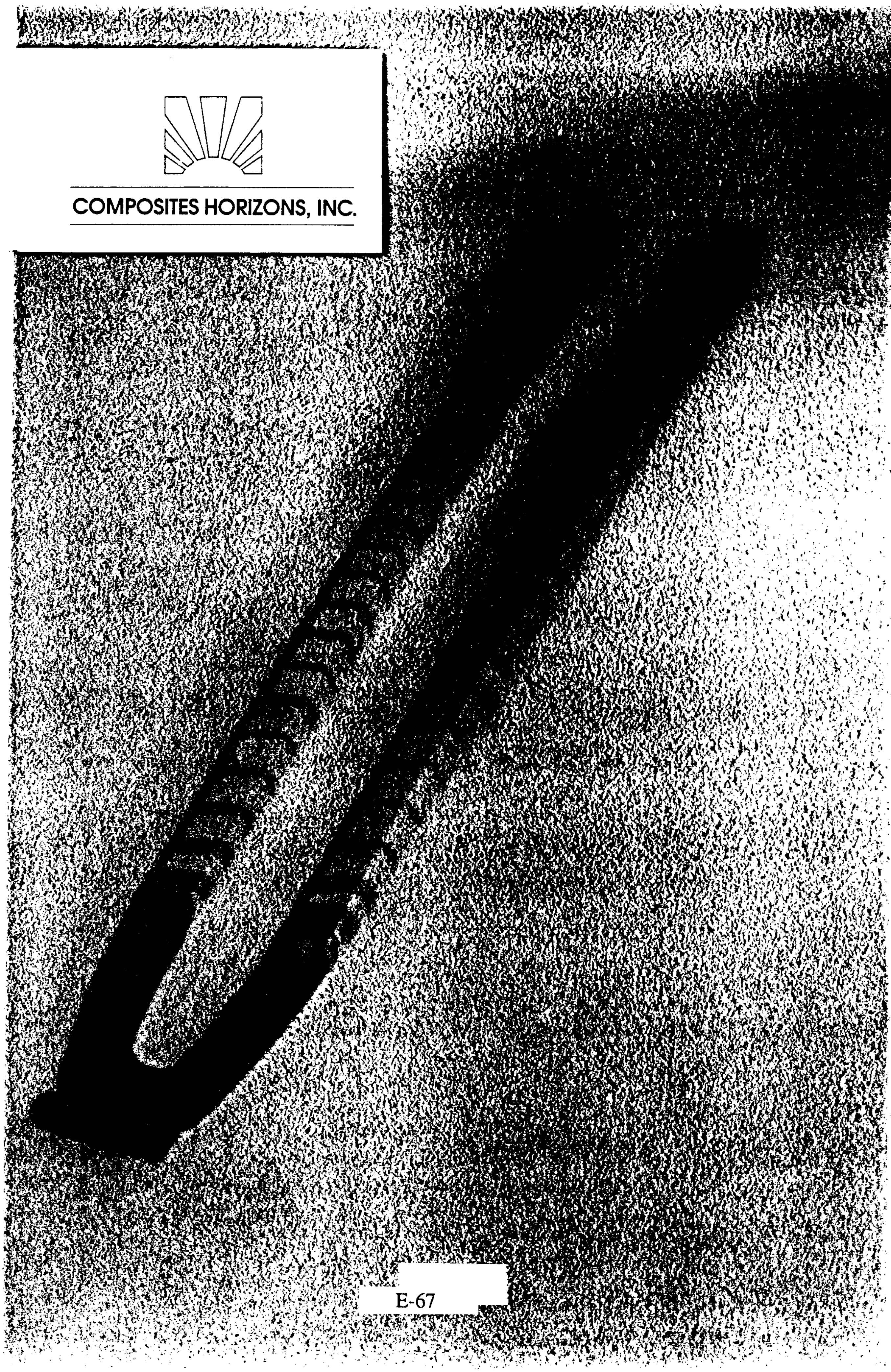

2.0 100 % Bulk Factor of Imidized PMR-15

Problem: PMR-15 bulk factor would prevent net shape molding of hat sections and induce wrinkles on outer skin during cure.

Solution: Two part imidization.

Inner Hat stiffened skin imidized separate from outer skin. Two halves combined during final cure.

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3.0 CTE Differential to 600° F

Problem: a) PMR-15 requires a 430° F imidization cycle.
b) PMR-15 requires a 600° F, 1,000 psi cure cycle.
c) CTE mismatch prevents net shape molding, and locks part onto tool during cool down.

CTE:	**Steel**	**6-8 x 10-6 in/in/°F**
	CF/PMR-15	**2 x 10-6 in/in/°F**

Solution: a) CF/PMR-15 Imidization tools sized to match CTE of steel at 430° F.
b) Hot loading of press cure cycle at 450° F.
c) Removal of part at 400° F.

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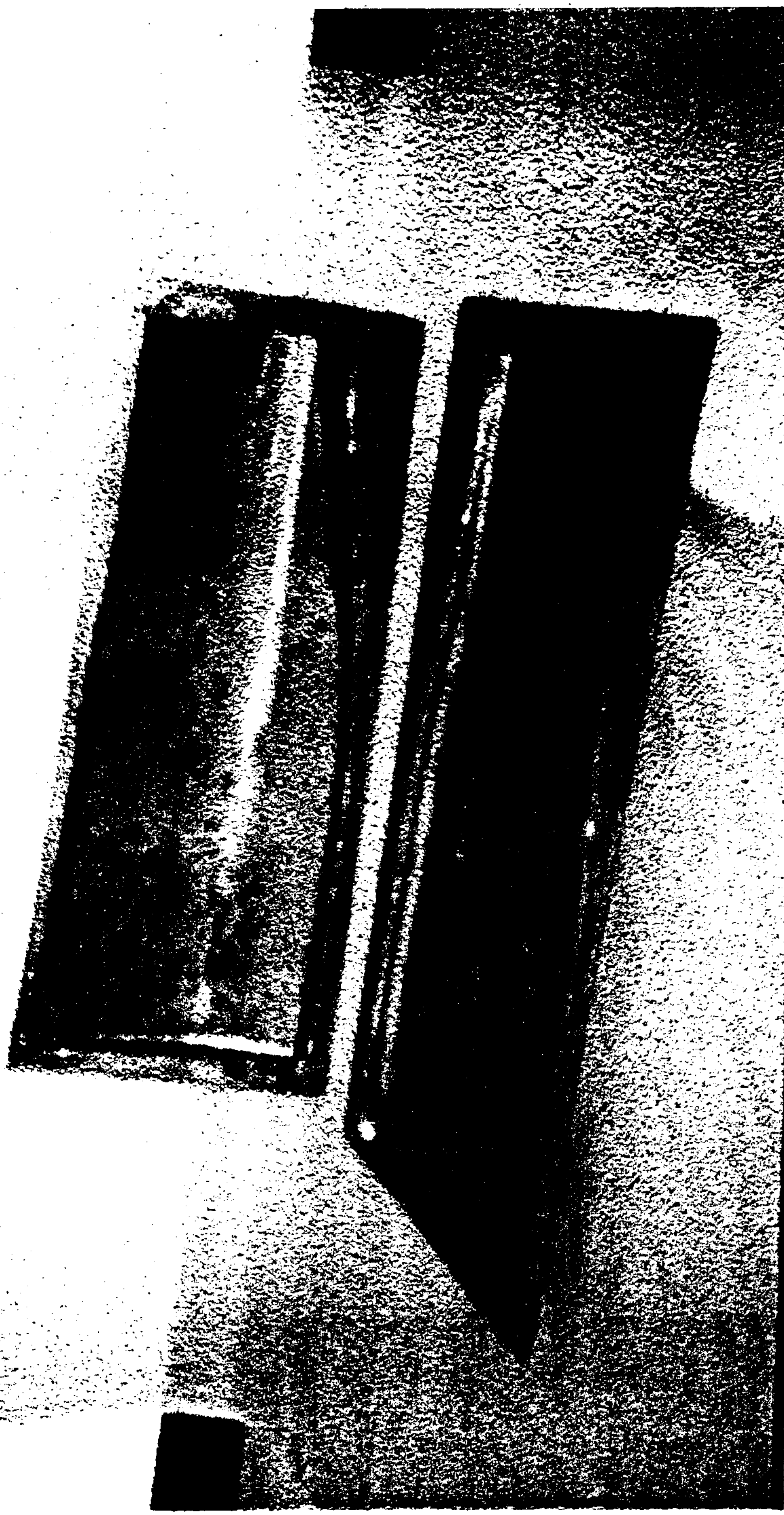

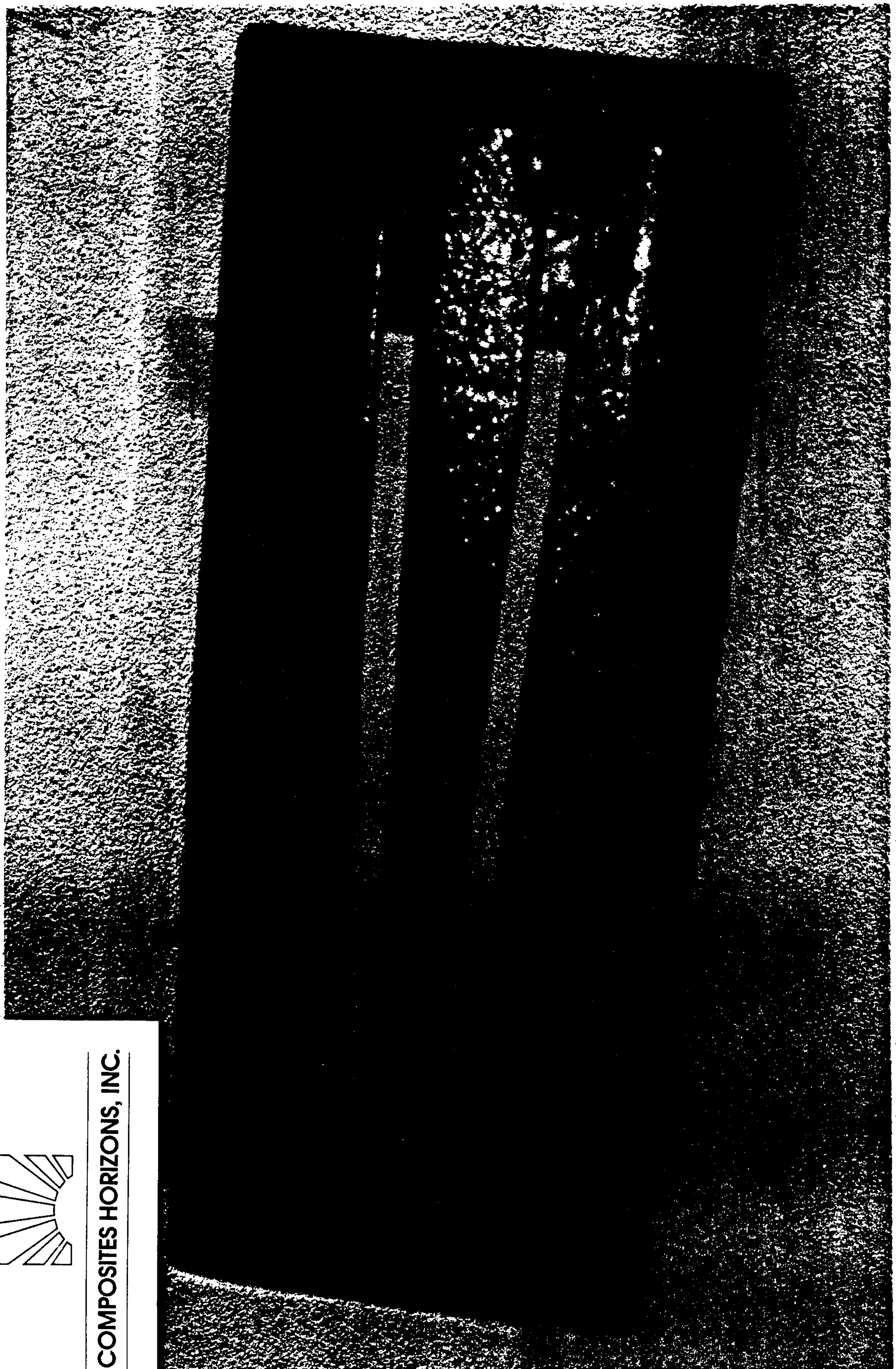

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4.0 8 Hour Standard PMR-15 Cure Cycle

Problem: PMR-15 standard cure cycle is 8-10 Hours.

Exhaust flap program rate to reach 5 parts/ day using one press and tool.

Solution: Optimized cure cycle resulted in 2.5 hours total time in the press.

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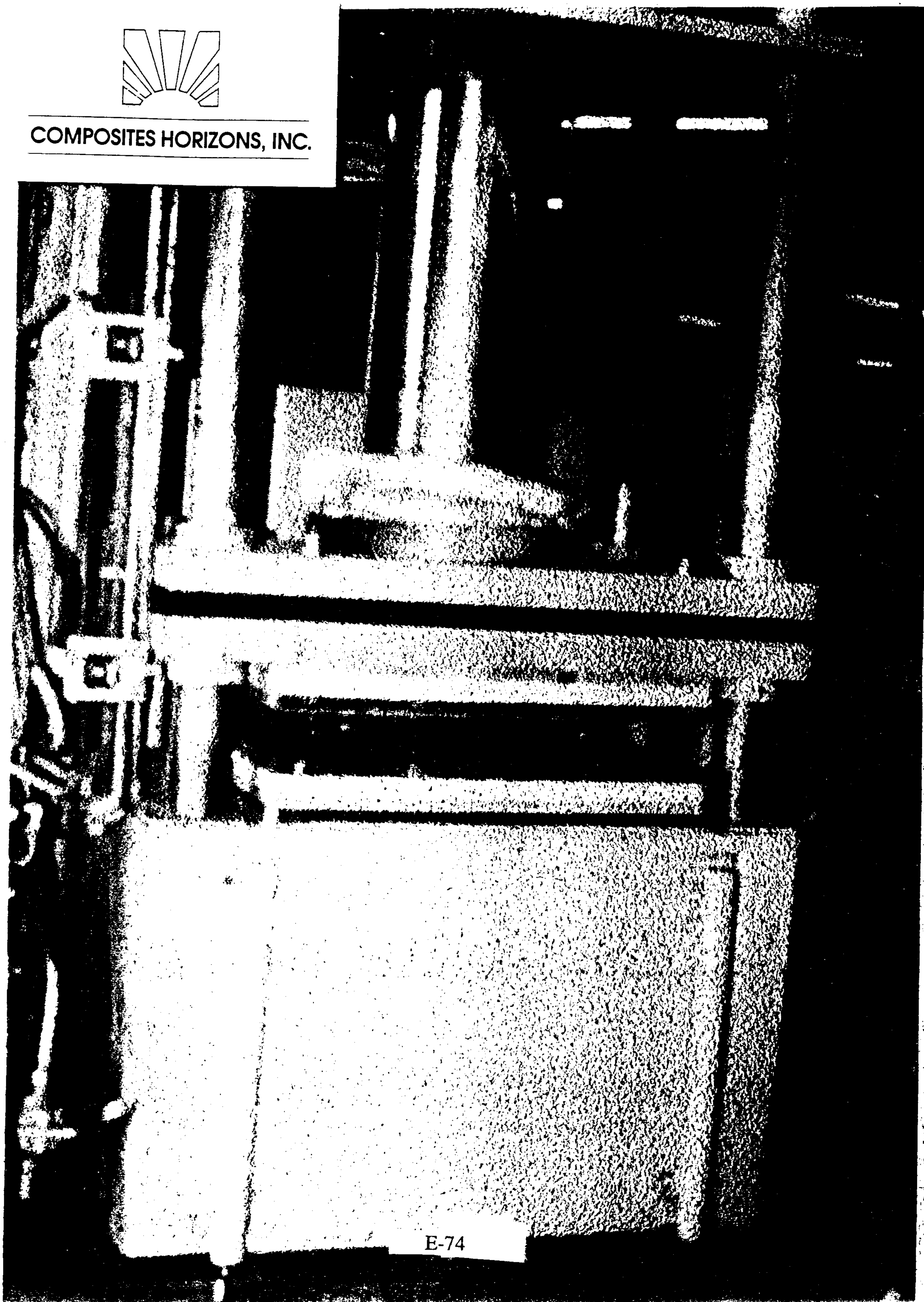

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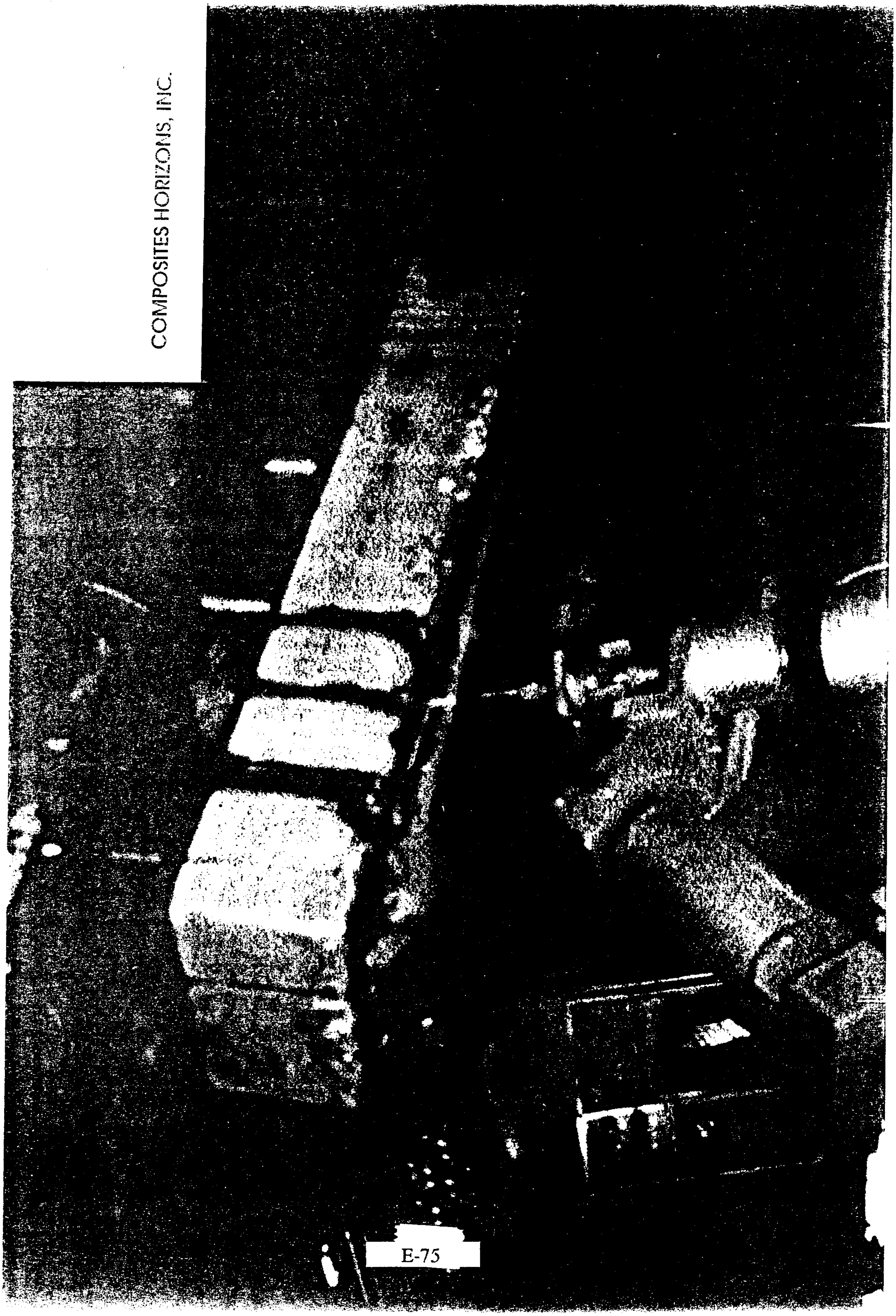


RTM for Composite Missile Airframe Production

The Opportunities of the 1980's are Gone!

- Large number of programs offering differing levels of complexity
- Requirement based on low cost at high production rates
- Competitive with Investment Castings
- Trade weight for cost
- Maximize structural integration
- Provide special technologies enhancements

  Examples: TSSAM, TMDE, AIWS (JSOW), MSOW, LRCSOW Programs

Opportunities of the 1990's and Beyond??

- Limited number of new starts or improvements
- Production requirements significantly lower and uncertain

  Funding for rate tooling enhancements even more limited
- Need to rely on the baseline, qualified RTM process, develop a critical manufacturing mass, not missile specific manufacturing technology--*DUAL USE*!

RTM is becoming Broadly Accepted for Manned Airframe and Engine Programs

- Key Airframe Program is the Lockheed/Boeing/USAF F-22
- Propulsion Systems Programs:
  - ARPA ACP Fan Exit Case
  - P&W JTDE Inlet Case
  - PW4084 Fan Spacer

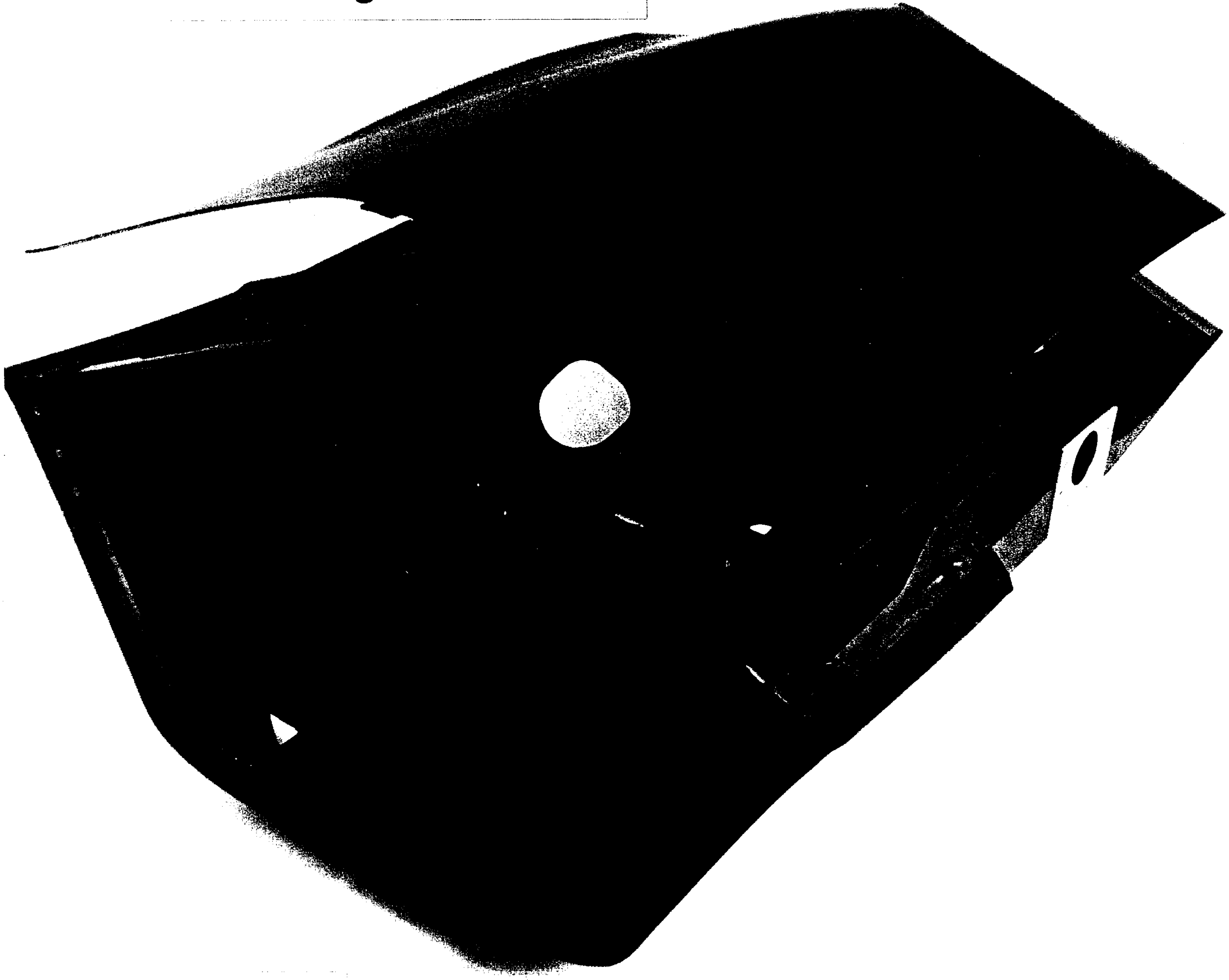
"These programs validate the process, materials, offer significant complexity, and provide a beginning production base for RTM"

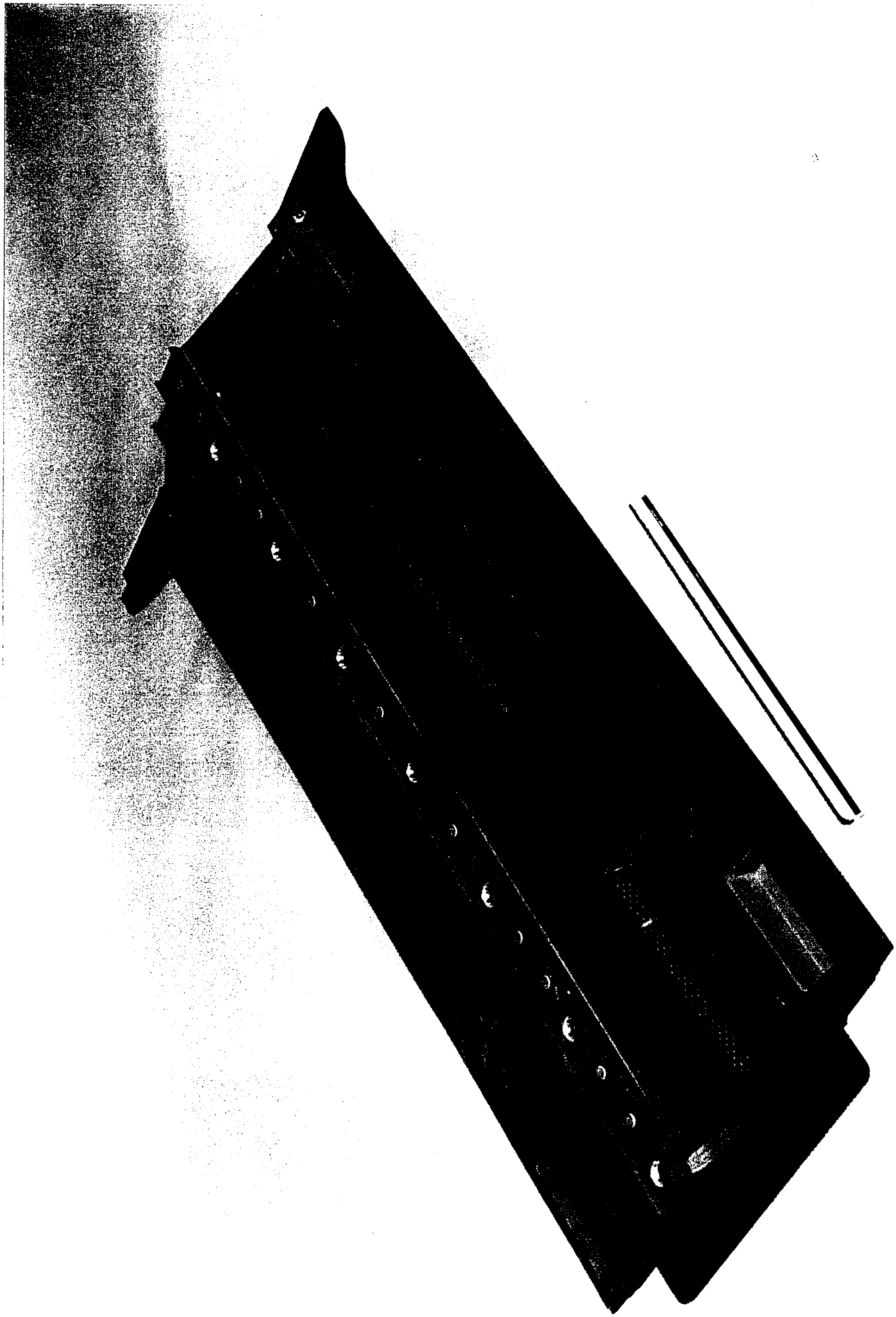
- Materials Data Base is growing
- RTM is Equivalent mechanically to Prepreg materials
- Baseline RTM Process is Defined, Robust and in place
  - Control by detail and rigid process specification
- Quality Levels meet the requirement of Primary structure
- Competitive with complex metal designs
  - Weight savings
  - Cost savings

Issues regarding RTM for Missile Systems Components

- Design
  - Traditional metal designs should not be cloned to be cost effective
  - Need to work technologies related to: Heat Transfer, Electrical shielding, fastener installation
- Cost
  - Are composites cost competitive with cast aluminum?
  - Willingness in the industry to pay for performance?
- Quality
  - Need to define quality requirements, up front, to truly understand the cost of the composite product!

TSSAM RTM Engine Module

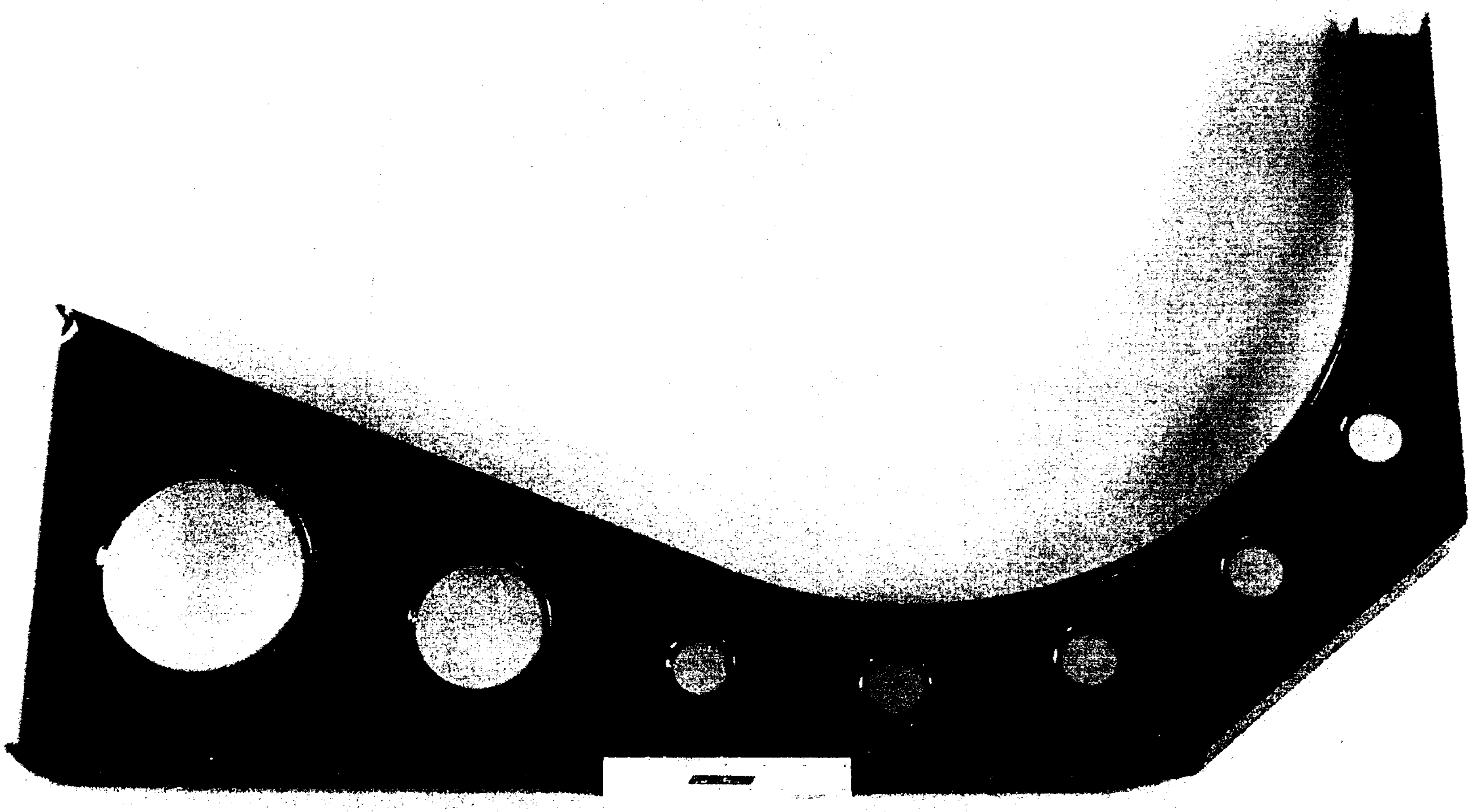




Dow-United Technologies Composite Products, Inc.

SINEWAVE SPAR

RTM FUSELAGE FRAME



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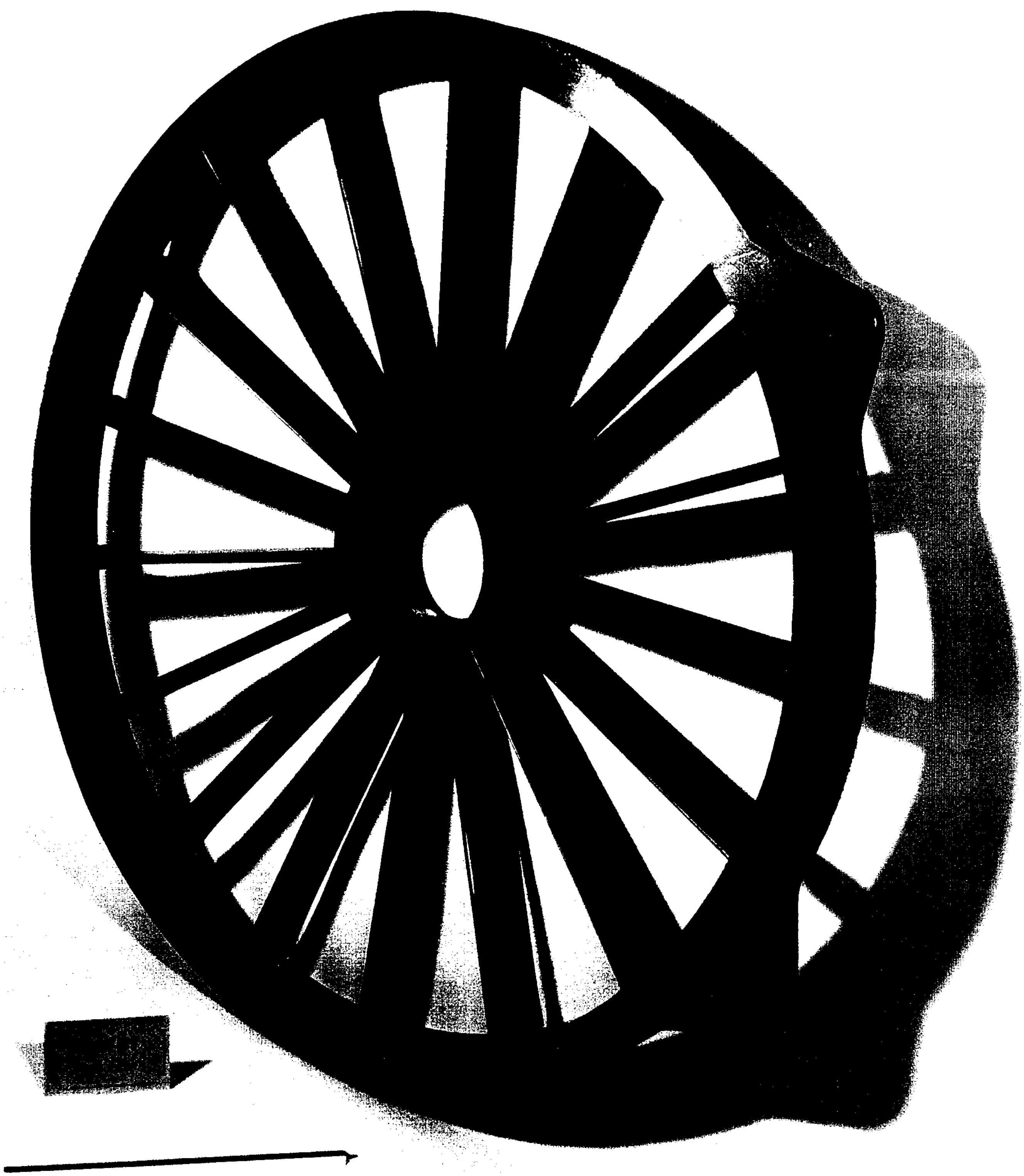
JTDE ENGINE INLET CASE



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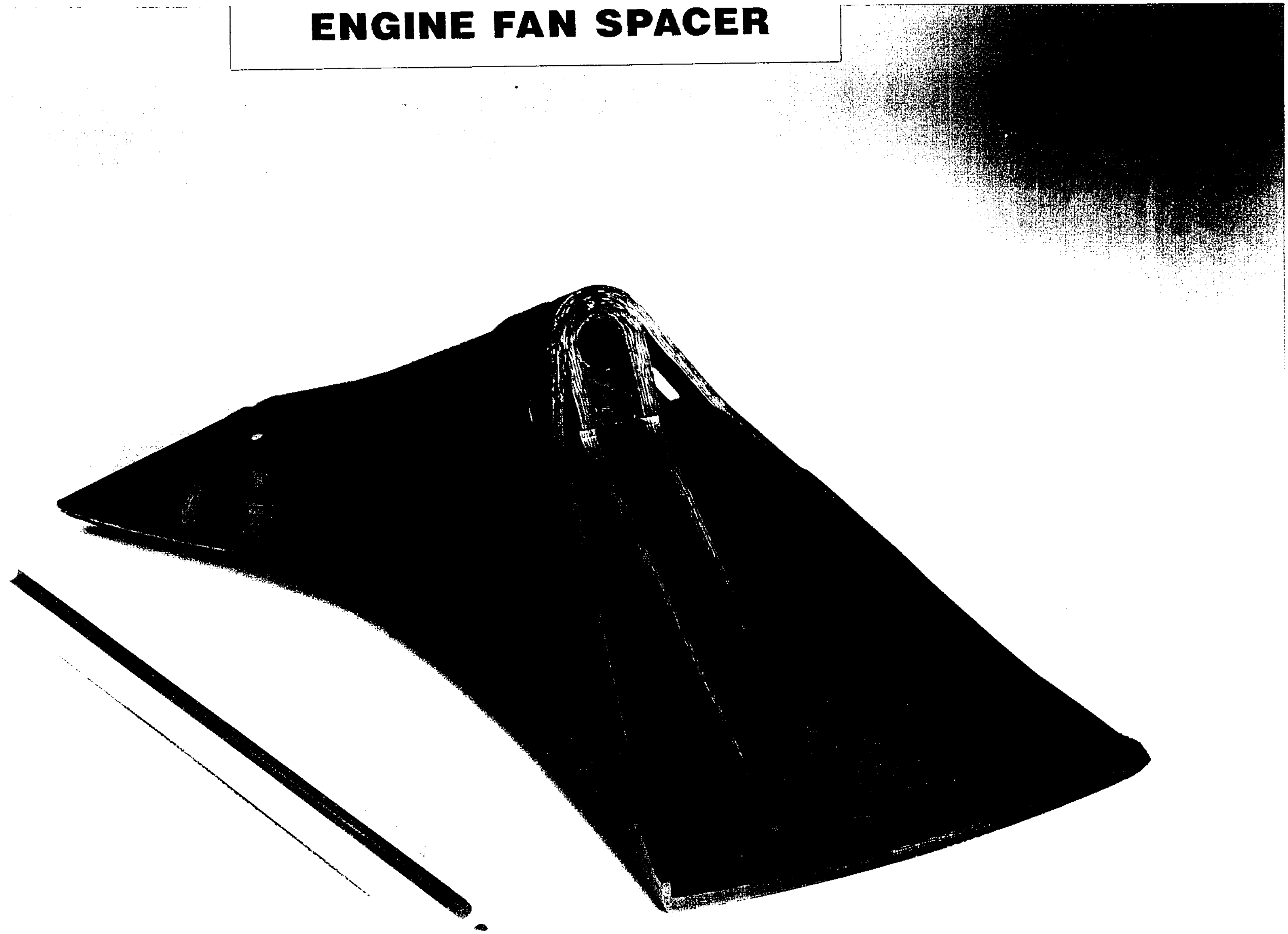
ENGINE FAN SPACER



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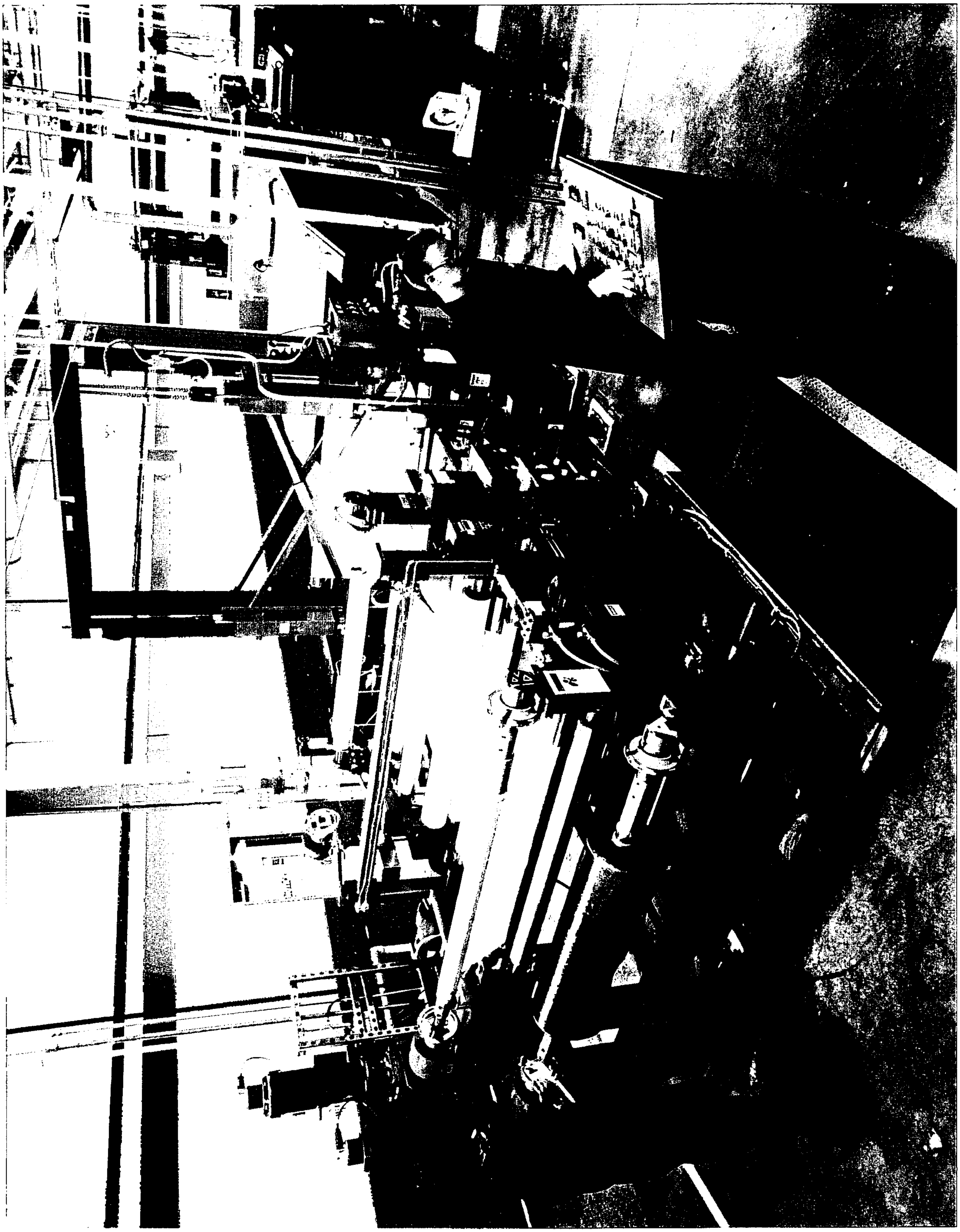
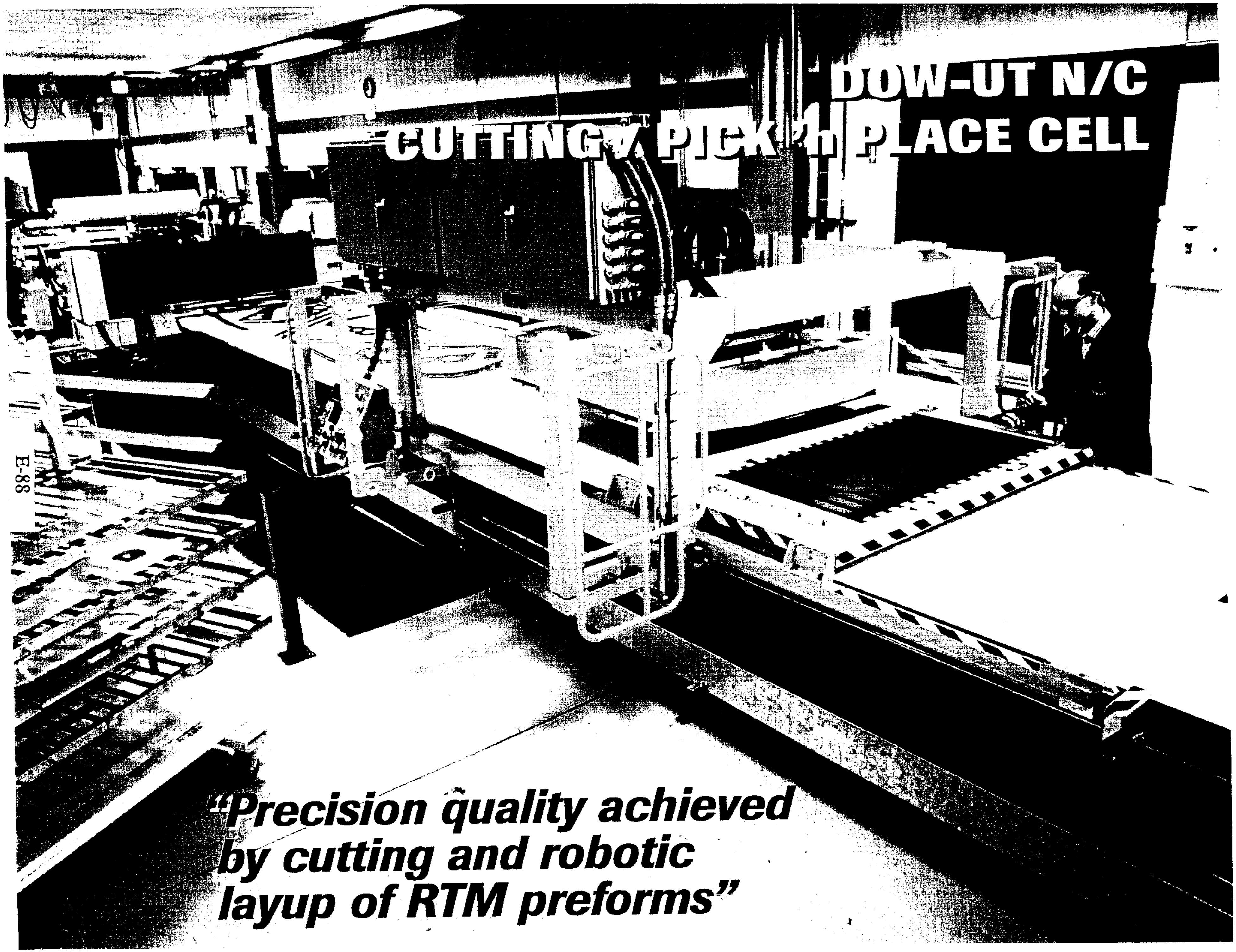
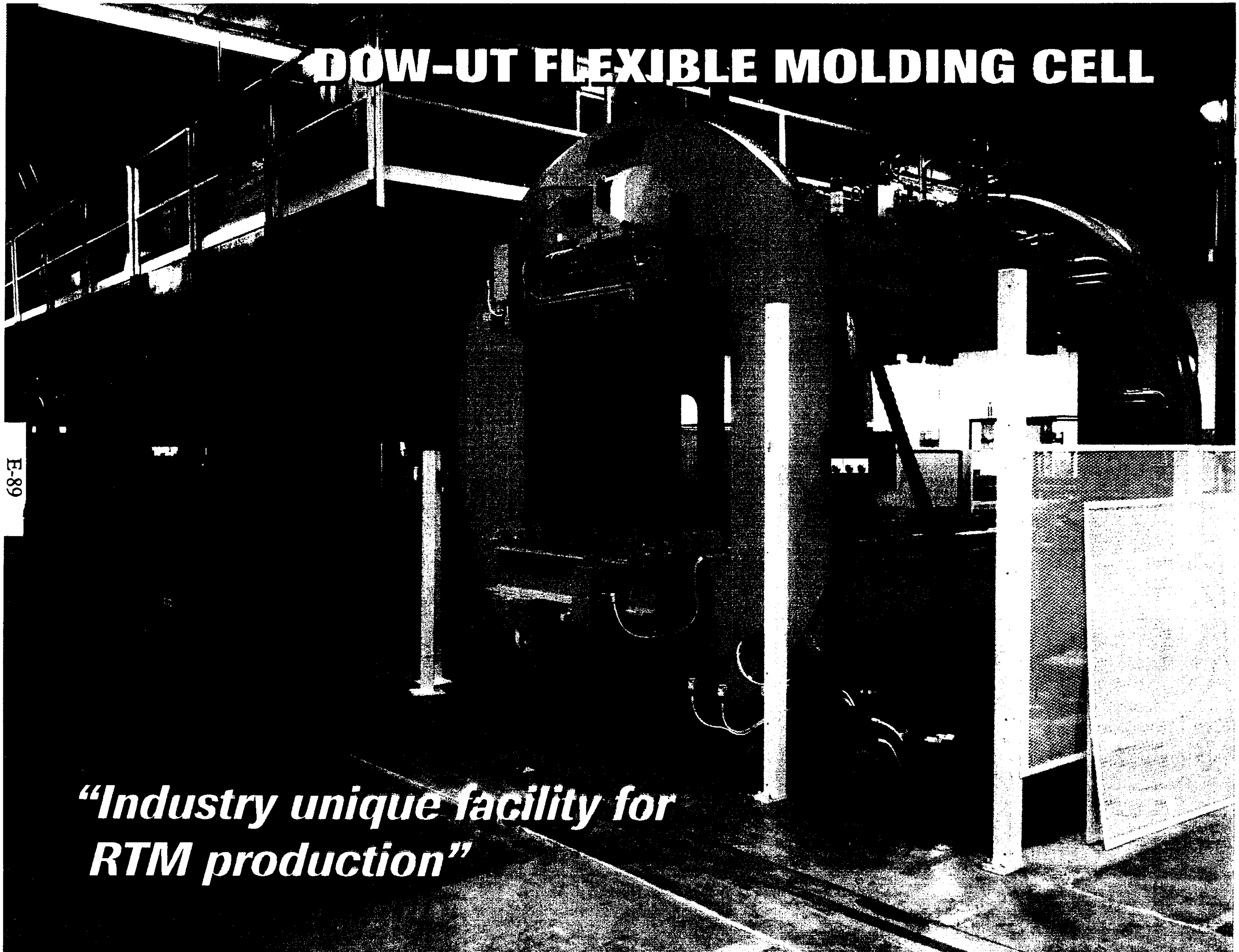
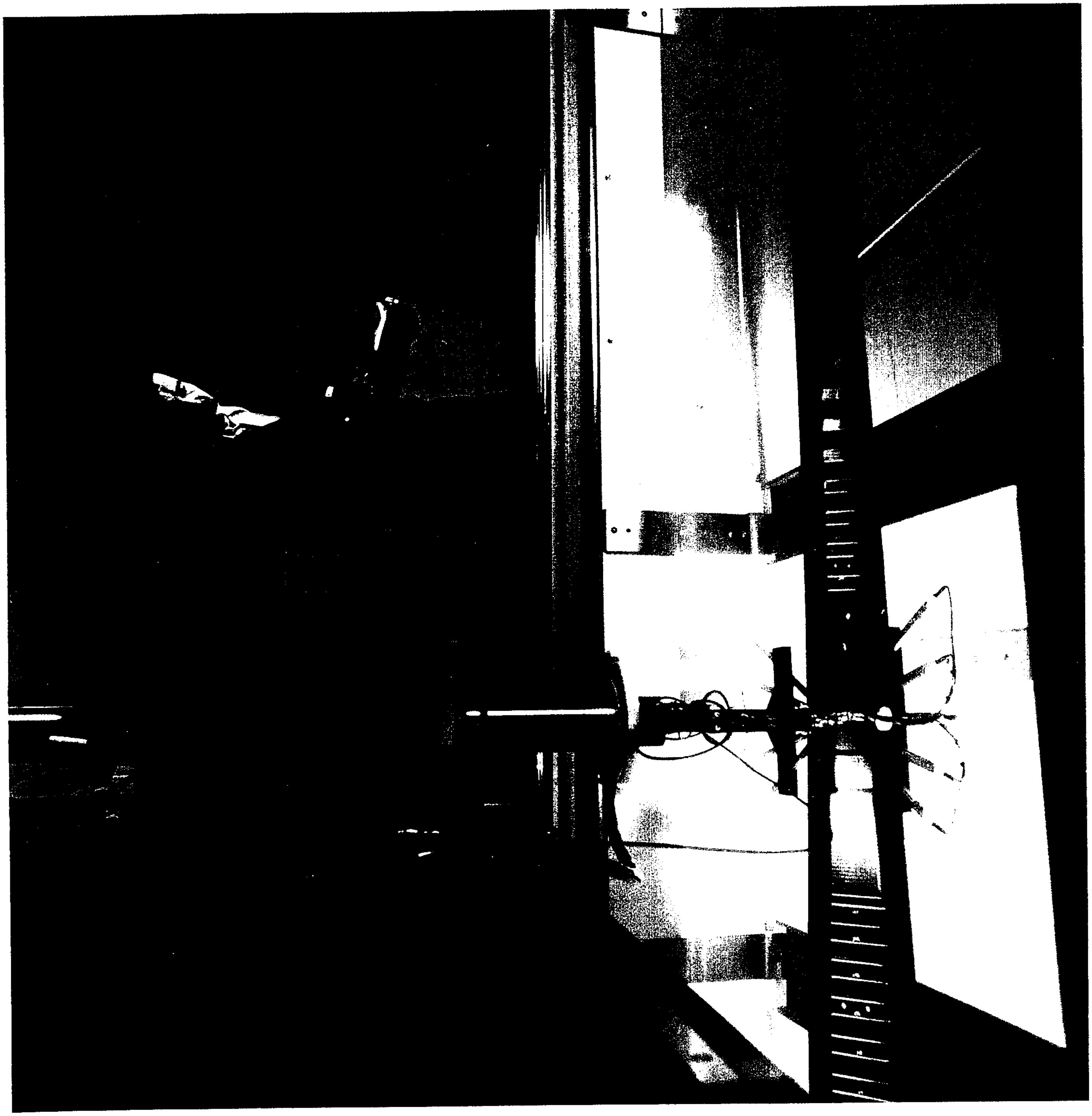


DOW - UNITED TECHNOLOGIES COMPOSITE PRODUCTS, INC.


DOW-UT N/C
CUTTING / PICK 'n PLACE CELL
"Precision quality achieved
by cutting and robotic
layup of RTM preforms"


DOW-UT FLEXIBLE MOLDING CELL
"Industry unique facility for
RTM production"



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BMDO/ARL-MD DEVELOPED MATCHED METAL NET MOLD FABRICATION TECHNOLOGY FOR INTERCEPTOR KKV STRUCTURES

Workshop on Closed-Mold Manufacturing of High Performance Composite Missile Structures

Hosted by the Institute for Defense Analysis, May 15-16
Washington, D.C.

Prepared By:

Joel Zuieback (SPARTA, Inc.)

G. Wonacott (Vanguard Composites Group)

Matched Metal Net Mold Technology Development Sponsored by BMDO Materials and Structures Program Under Contract to the U.S. Army Research Laboratory-Materials Directorate

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PRESENTATION AGENDA

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- OVERVIEW OF BMDO/ARL-MD DEVELOPED MATCHED METAL NET MOLDED FABRICATION TECHNOLOGY
- MATCHED METAL NET MOLDED FABRICATION TECHNOLOGY MATERIALS AND PROCESS ISSUES
- MATERIALS AND FABRICATION DEVELOPMENTS ENHANCING TECHNOLOGY INSERTION IN BMDO/ARMY SYSTEM ELEMENTS
- MATCHED METAL NET MOLDED COMPONENTS FULLY QUALIFIED FOR FIELDED SYSTEMS (JAVELIN)
- GLOBAL DESIGN AND MATERIALS ISSUES RELATED TO COMPOSITES
- CONCLUSIONS AND RECOMMENDATIONS

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MATCHED METAL NET MOLDING OVERVIEW

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OBJECTIVE: REDUCE COST OF PRECISION, COMPOSITE MISSILE COMPONENTS BY REDUCING PARTS COUNT, ELIMINATING SECONDARY OPERATIONS, AND INCREASING REPRODUCIBILITY

Concurrent Engineering: • Prime Contractors, Fabricators, Materials Suppliers Team • Electronics Interfaces • Solid Modeling (e.g., Pro-Engineer) Provides Common Data Base	**Tooling:** • Pro-Engineer Solid Modeling Tool Enables complex geometric shapes • Advanced Tooling Enables More Complex Geometric Shapes to Be Fabricated Reducing Parts Count and Integrating Multifunctionality
Rapid Prototyping: • Necessary for Composites Insertion Early in Product Development Cycle • Converging on CMFP Design Earlier in the Design Cycle Saves Product Development Costs • Enables Rapid Changes to Existing Tooling Designs	**Process Verification:** • Minimize End Item Inspection • Composites Oriented Inspection Procedures • Matched Metal Tooling Extremely Reproducible Process (Verified Using SPC) • Process Science Quantifies and Correlates Process Parameters with Laminate Quality (Cosmetics, Void Content, and Mechanicals)

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Process Issues

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Tooling

- Mold Design Flexibility for Variances in resin Types/Quantities/Architecture
- Rigidity of Tooling Designs and Materials to withstand High Mold Pressures
- Mold Precision
- Uniform Heating and Cooling throughout the Mold
- Long Leadtime to Fabricate the Complex Molds
- Mold Maintenance - Cost may Prohibit Multiple Molds
- Overall Mold Size Limitations

Part Lay-up

- Long Lay-up Times/Labor Content
- Holding Non-Resin Based Materials/Cores in Position During Molding Process
- Ability to Rapidly Debulk Material on Complex Parts
- Maneuverability of Tooling During Lay-Up Process

Part Curing/De-Molding

- In-Process Monitoring Limitations - “Part Recovery”
- In demolding, the risk of damaging the part while removing an often heavy tool
- Procedure to "~~l~~ump" part during use without risking pinching of fibers

b

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MATCHED METAL NET MOLDED EXAMPLE

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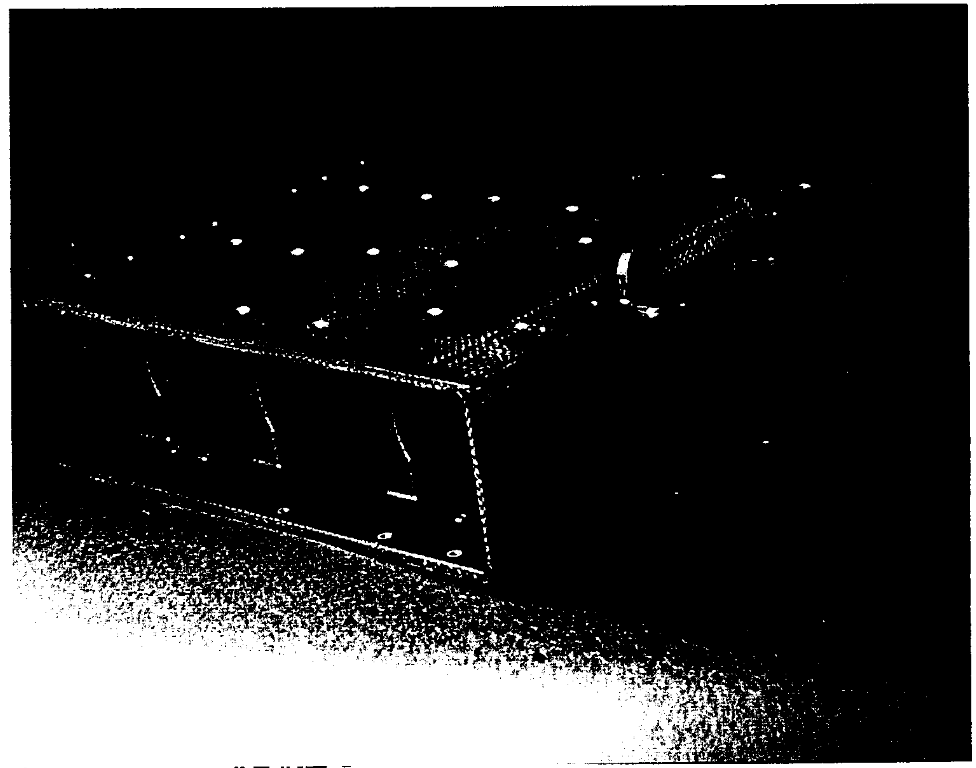

FEATURES

- One Piece, Net Molded Primary Structure
- Internal Ribs Conformal to Thermal Batteries
- Internal Ribs Co-Cured (Mechanically Locked) to Face Sheets
- Foam Sandwich Integrated into Face Sheets to Reduce Weight
- Fastener Inserts Integral to Foam Sandwich Face Sheets
- High Strength Lugs Integral to Box; Capable of Transmitting Primary Loads

COST

- Baseline Machined Aluminum ≈ $3,000 ea.
- Composite Design ≈ $2,700 ea.

WEIGHT COMPARISON

- Machined Aluminum: 10.8 lbs
- Composite Design: 4.8 lbs (56% Savings)

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LOW COST MULTIFUNCTIONALITY USING MATCHED METAL NET MOLDING

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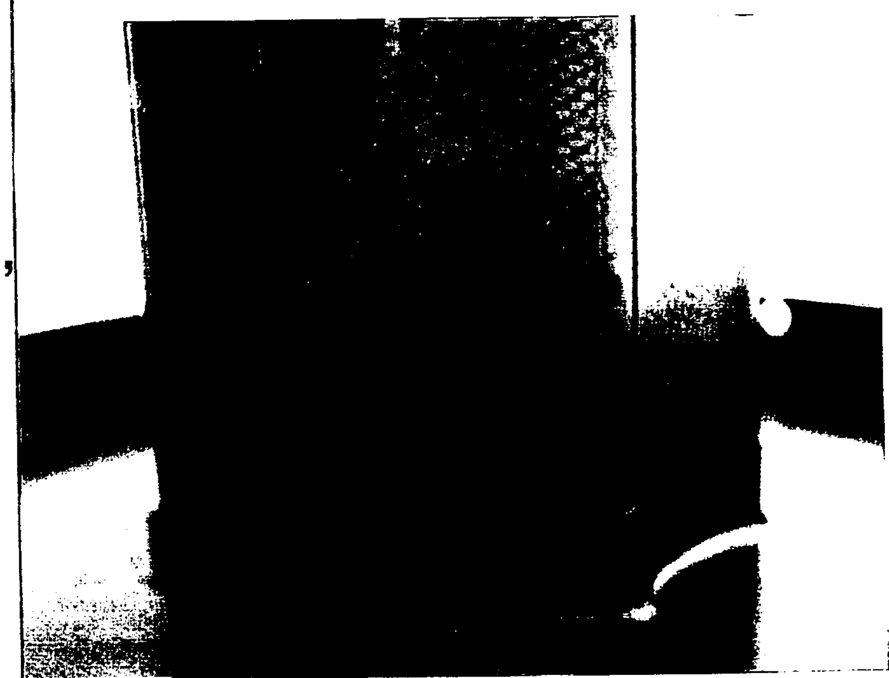
MULTIFUNCTIONALITY: INCORPORATES MATERIALS INTO COMPOSITE WHICH ENHANCE DAMPING, ELECTRICAL, THERMAL, AND SHIELDING CHARACTER-ISTICS OF COMPOSITE COMPONENTS AND STRUCTURES

- **DAMPING**- VISCO ELASTIC MATERIAL
- **ELECTRICAL**: COATED FIBERS
  THERMAL: HIGH THERMAL CONDUCTIV-ITY PITCH FIBERS
- **SHIELDING**: ONE PIECE CONSTRUCTION, OATED FIBERS, PARTICULATES

MATCHED METAL OFFERS THE POT-ENTIAL TO EMULATE METALS AT VERY LOW COST; ONE STEP FABRI-CATION AVOIDS COSTLY SURFACE PREPARATION- KEY ISSUE IS VERI-FICATION OF QUALITY OF MULTI-FUNTIONAL COMPOSITE MATERIAL


Close-up of Axial Slits in Successfully Fabricated Generic Exo-KKV Structure

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MATERIALS ISSUES

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Materials

- Material Formulation s for MMNM - Short pressure and/or heating cycles
- Supplier able to hold tighter more consistent tolerances on prepregs
- Better "Wet Out" of heavier Fibers/Fabrics

Support

- Shorter Delivery Cycles - "Ready Inventory"
- Process/Material Integration - How can process change to work better w/mat"ls
- Longer Material Certification Period
- Availability of "Working Samples"

Other

- Common Basis to Compare "Same Materials" Vendor-to-Vendor

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DEVELOP CLOSED-MOLD EARLY IN PRODUCT DEVELOPMENT CYCLE

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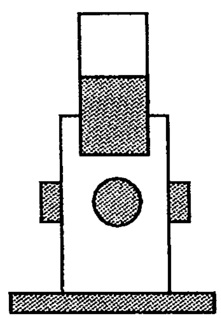
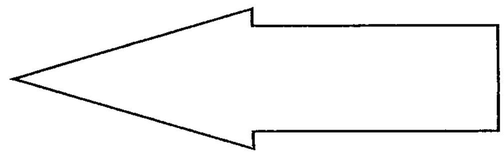
DEM/VAL (1-2 YRS)	EMD (3-5 YRS)	LRIP (2-4 YRS	PRODUCTION (5-10 YRS)

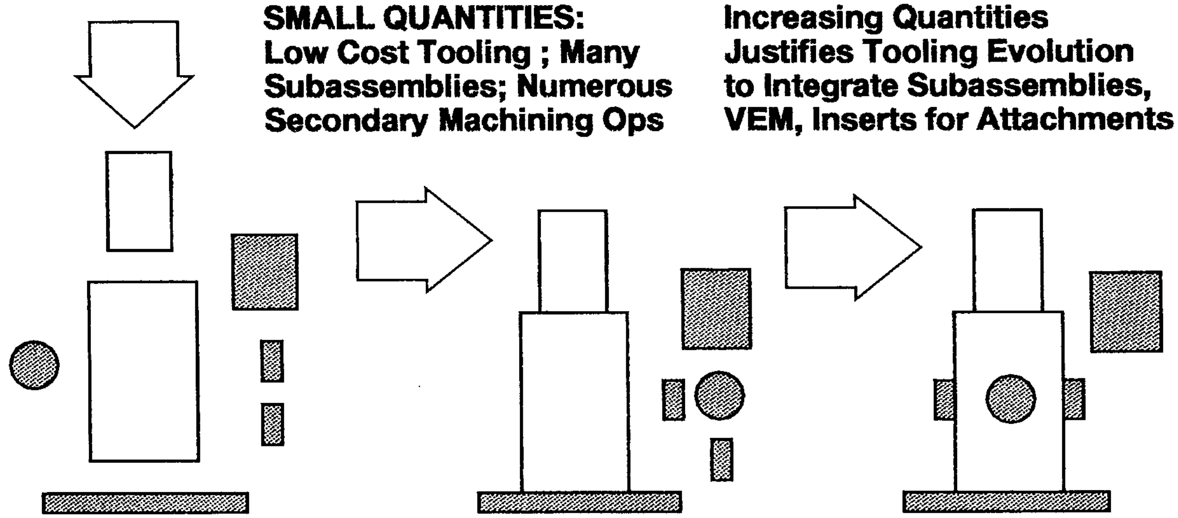


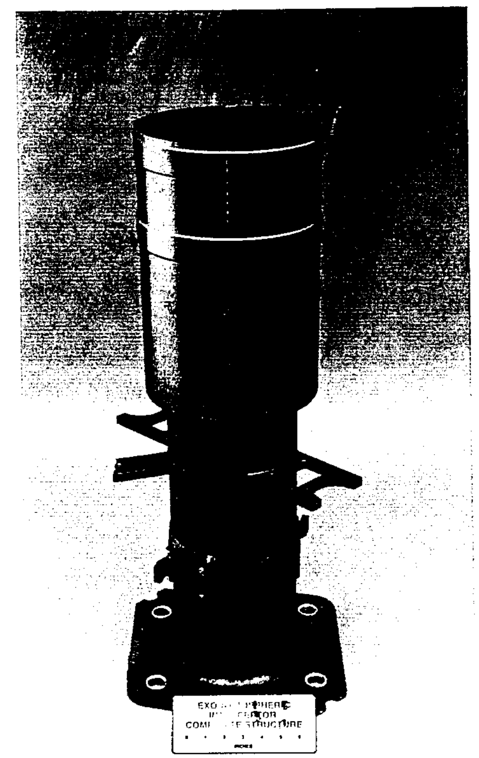
Develop a One Piece Net Molded Design with Integral VEM and Inserts for Seeker Assemblyu Support



SMALL QUANTITIES: Low Cost Tooling ; Many Subassemblies; Numerous Secondary Machining Ops

Increasing Quantities Justifies Tooling Evolution to Integrate Subassemblies, VEM, Inserts for Attachments





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SUCCESSFUL INSERTION OF COMPOSITES INTO JAVELIN SYSTEM

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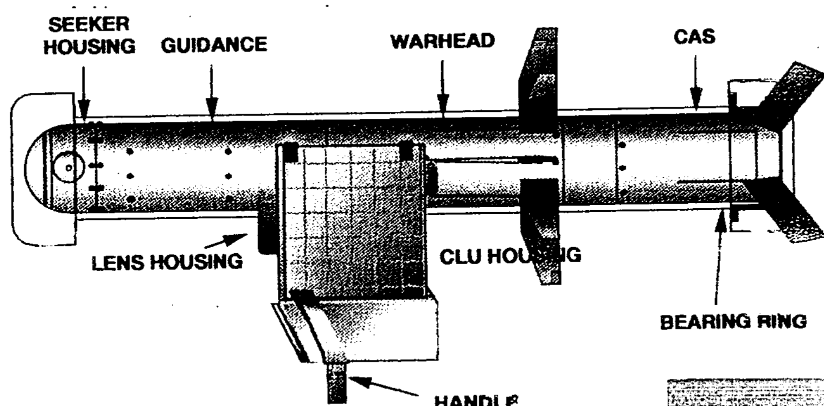
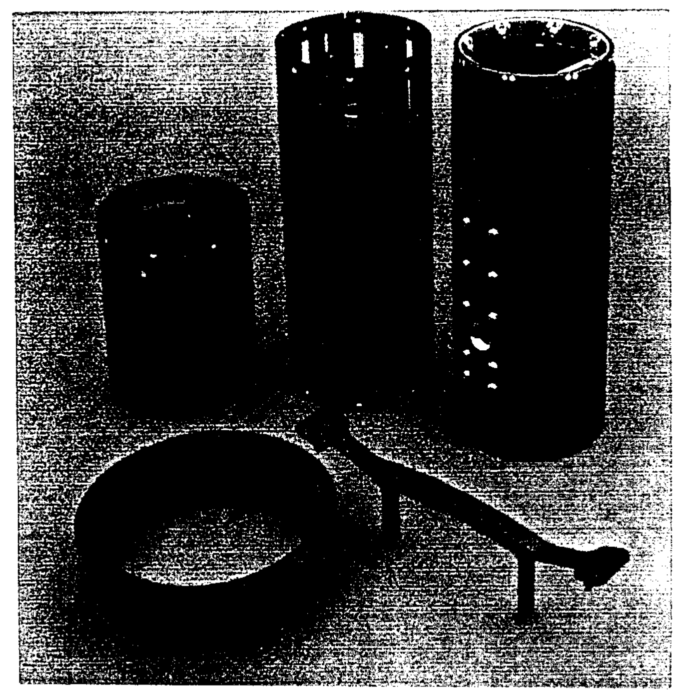


COMPOSITES PERFORM

- 5 COMPOSITE COMPONENTS ARE FULLY QUALIFIED
- > 50 LIVE FIRINGS VERIFY PERFORMANCE
- CRITICAL LOAD SPECS MET
  - HANDLING DROP SHOCK (3 FT)
  - STATIC STRUCTURAL LOADS
  - SAFETY HANDLING DROP SHOCK (5 FT)
  - VIBRATION (TACTICAL AND CARGO
- PRODUCTION PARTS THROUGH 1995 > 8720 UNITS



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CONCLUSIONS AND RECOMMENDATIONS

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- BMDO/ARL-MD HAVE SUCCESSFULLY DEMONSTRATED THE MATCHED METAL NET MOLD PROCESS FOR INTERCEPTOR KKV STRUCTURES AND COMPONENTS
- INITIAL MISSILE APPLICATION IS JAVELIN CURRENTLY IN LOW RATE PRODUCTION
  - JAVELIN WILL PROVIDE EXTENSIVE DATA BASE AND FIELD USE EXPERIENCE ON COMPOSITES
- INTRODUCTION OF COMPOSITES EARLY IN PRODUCT DEVELOPMENT CYCLE IS CRUCIAL
  - TEAM APPROACH
  - SOLID MODELING COMMON DATA BASE
  - ELECTRONICS INTERFACE

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CONCLUSIONS AND RECOMMENDATIONS

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- THERE ARE ISSUES TO BE RESOLVED
  - PRIMARILY TOOLING COSTS FOR EARLY DEVELOPMENT PHASES
  - MORE PROCESS SCIENCE WOULD LEAD TO PRODUCT IMPROVEMENTS
  - JAVELIN FIELD EXPERIENCE WILL PROVIDE INVALUABLE DATA BASE FOR FUTURE DEVELOPMENT
- FUTURE INVESTMENT IN THE MATCHED METAL NET MOLD PROCESS WILL PRODUCE PAYOFFS
  - FUTURE TECHNOLOGY DEVELOPMENT SHOULD FOCUS ON THREE AREAS...
    1. PROCESS SCIENCE TO BETTER UNDERSTAND WHAT HAPPENS TO PREPREG IN A TOOL WITH A VERY COMPLEX GEOMETRIC SHAPE
    2. MULTIFUNCTIONAL MATERIALS DEVELOPMENT AND DEMONSTRATION TO ENHANCE COMPOSITE PERFORMANCE AND MAINTAIN QUALITY
    3. INTEGRATED STRUCTURES (E.G., PROPULSION, ENCLOSURES)

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13. ABSTRACT *(Maximum 180 words)*

LtCol Michael Obal of the BMDO Materials and Structures Office sponsored this workshop to promote communications among the participating groups and to identify technical issues and limitations associated with closed mold manufacturing of high performance polymer composite components for missile structures. Some of the identified issues include limited material and process specifications, trial and error approaches to tooling/mold design, lack of manufacturing methods to integrate other features and functions into composites, high costs of preform fabrication, lack of high temperature resins, and absence of standardized test methods, among a number of others. That little to no design allowable data, in particular missile-specific design for operational environments, are available appears to be one of the significant factors limiting use of composites by missile designers. Recommendations for future BMDO efforts include the support of (1) prime contractors and material suppliers, (2) programs to develop, demonstrate, and test multi-functional structures, and (3) programs to develop relevant design data on specific materials/components via carefully selected experiments, possibly including full-scale ground and flight tests.

14. SUBJECT TERMS
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